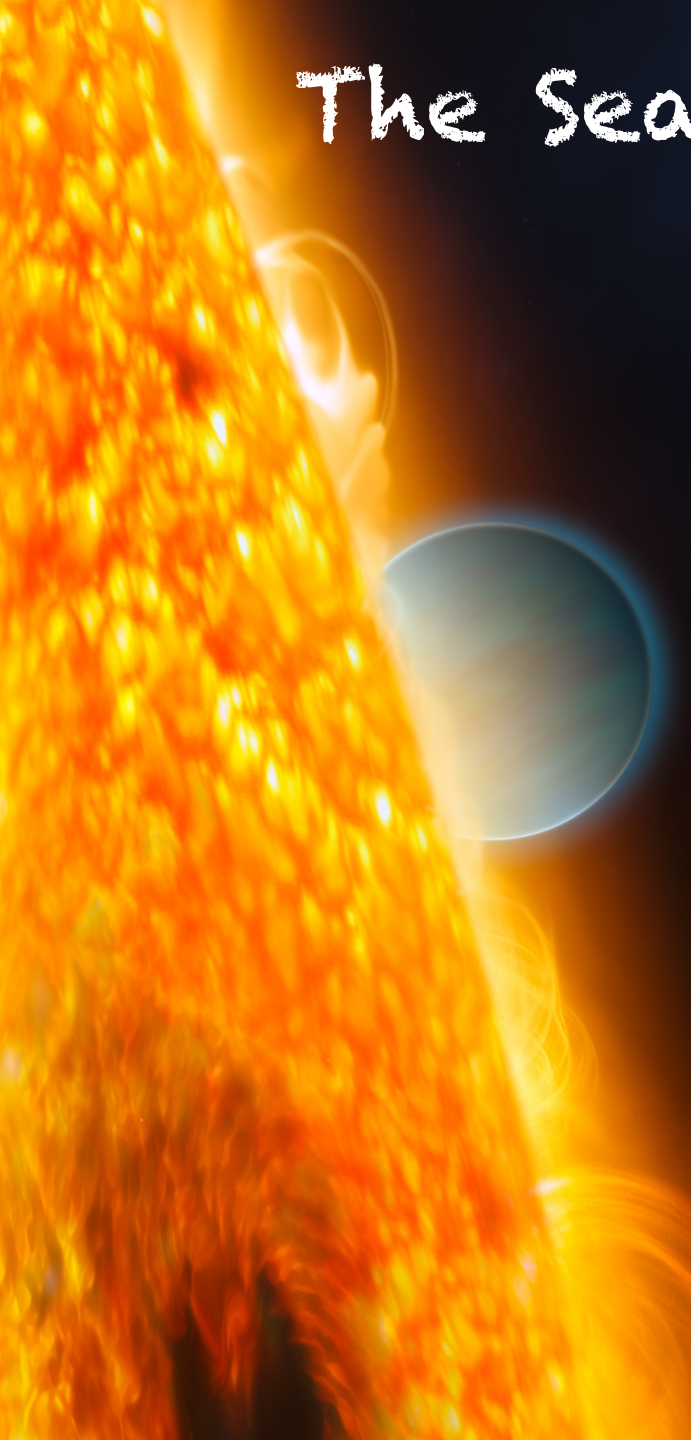
Remote-Sensing Biosignatures

Santander Astrobiology 2013

Prof Victoria Meadows, University of Washington

The Search for Habitable Planets



890+ Confirmed Extrasolar Planets

~113 Confirmed Multi-planet Systems

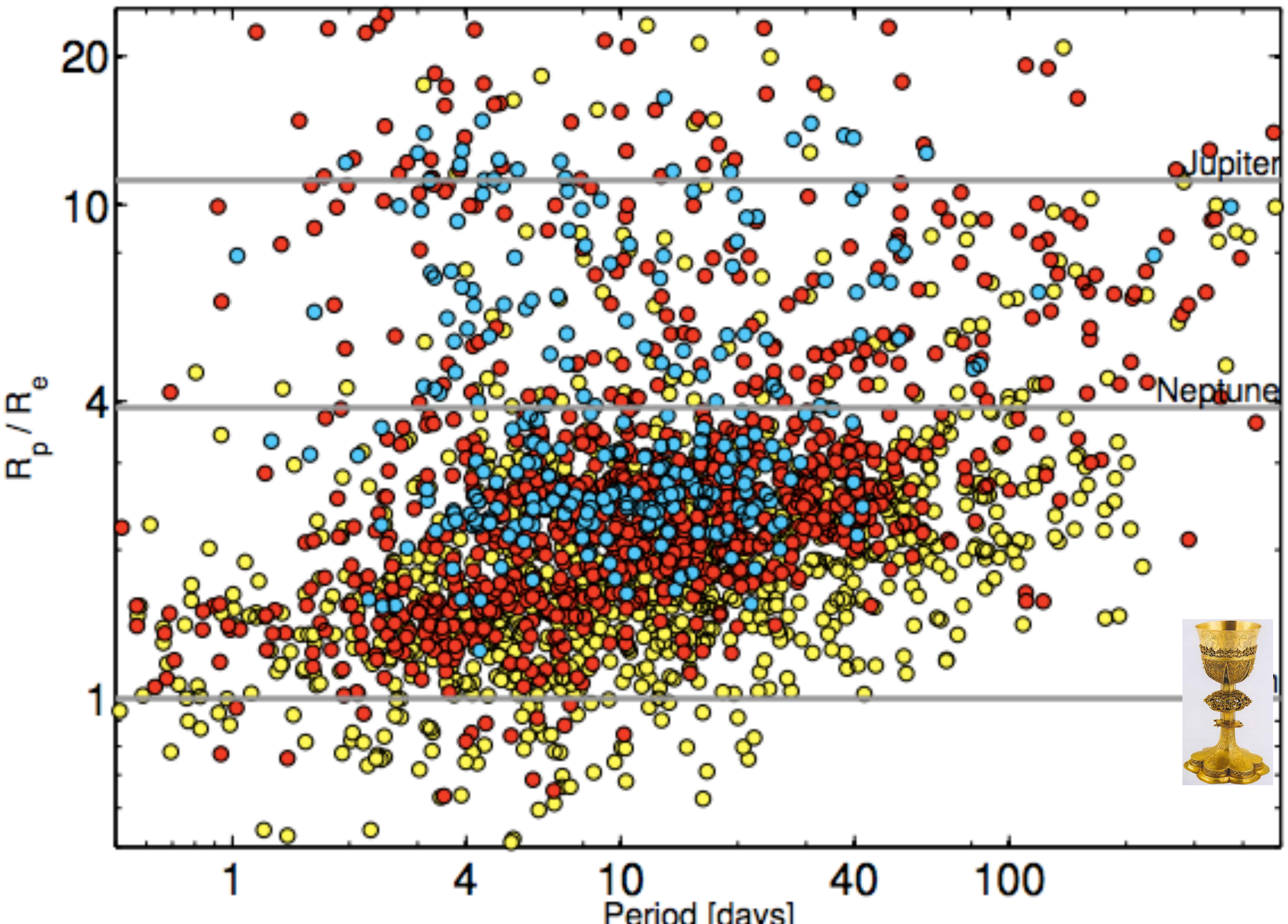
~ 120 planets have $M<10M_{Earth}$

Many are in the habitable zone of their parent stars.

A true Earth analog has yet to be found

– But it won't be long!

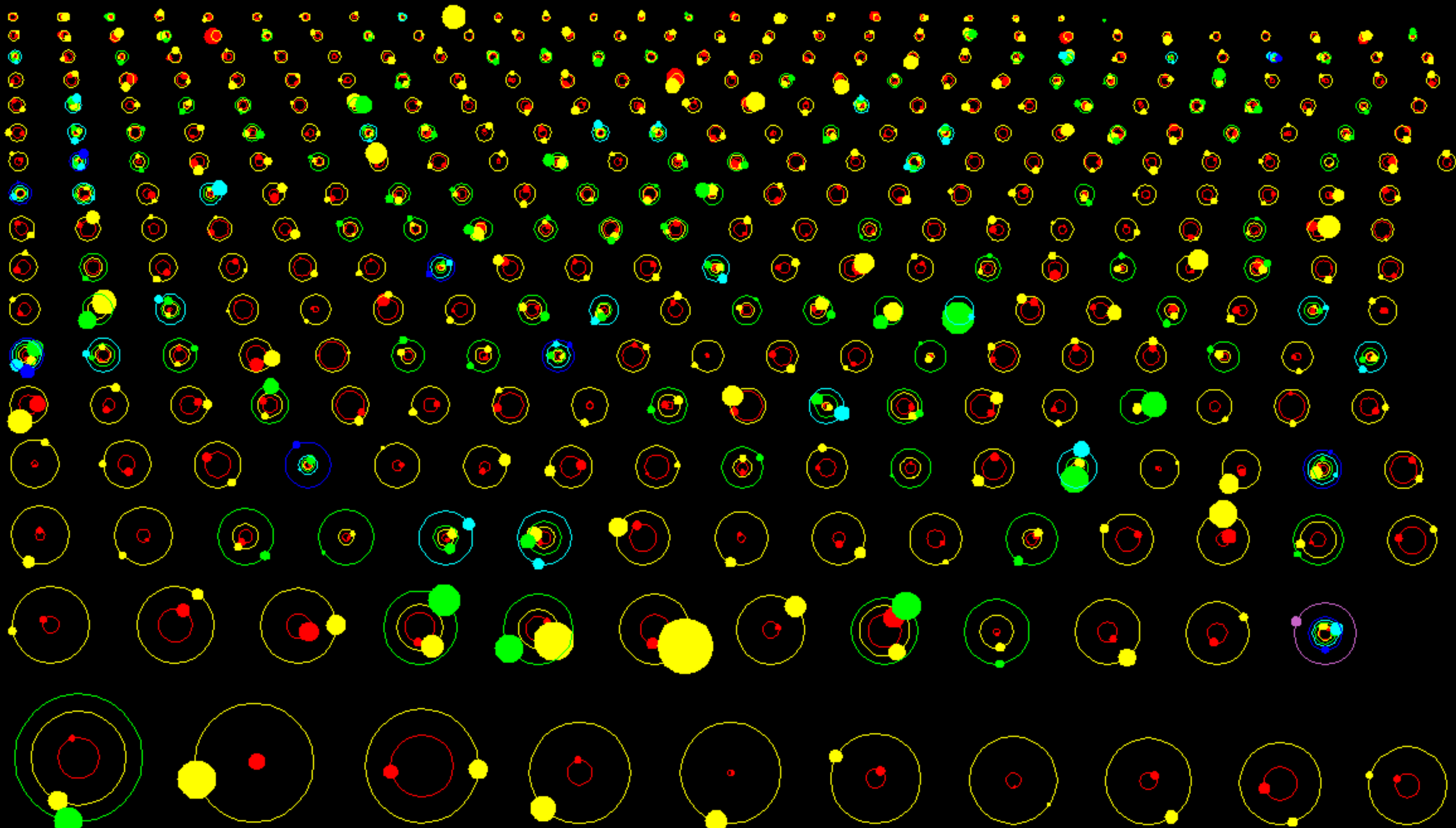
Kepler Candidates



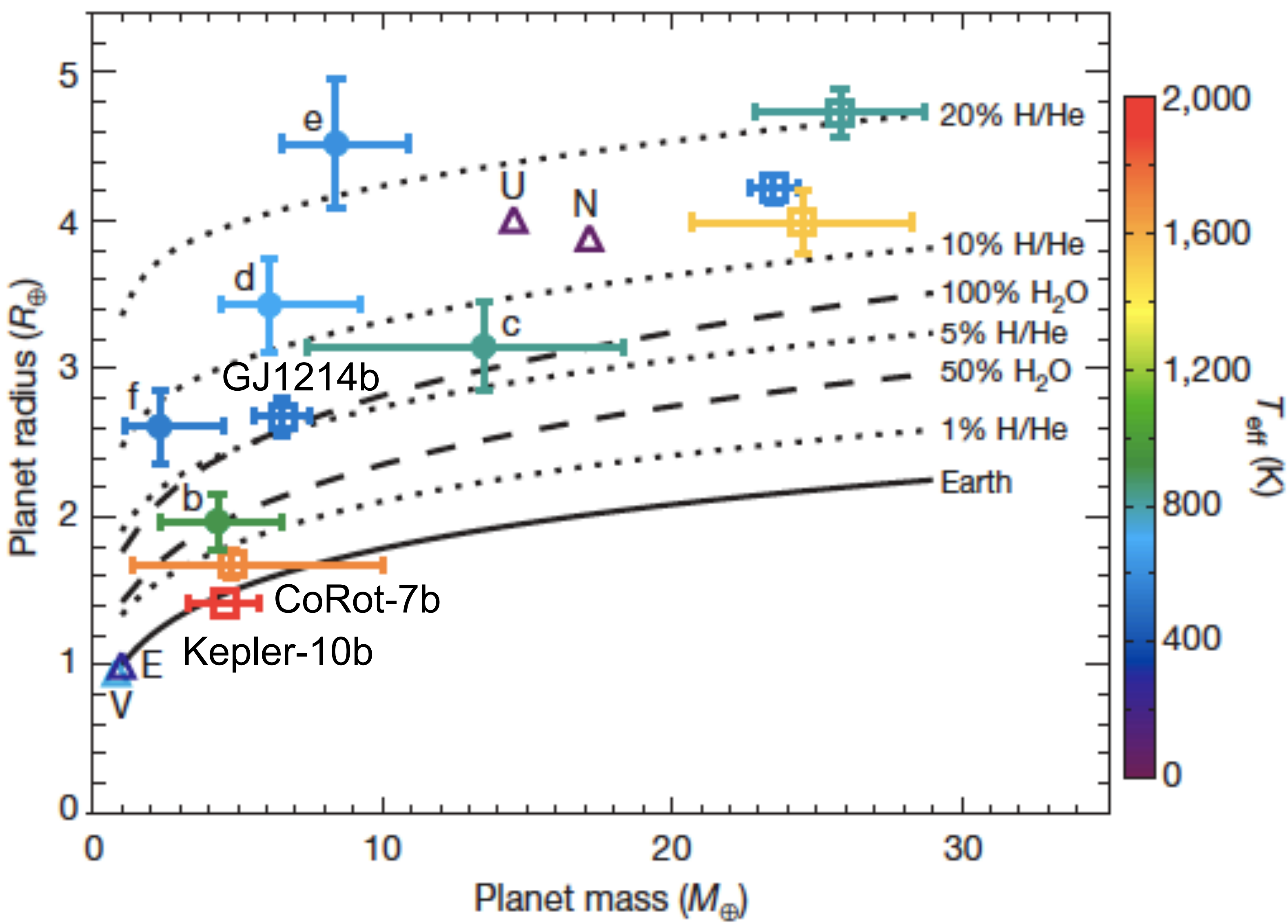
Batalha et al., 2012

The Kepler Orrery II

t[BJD] = 2454965 D. Fabrycky 2012

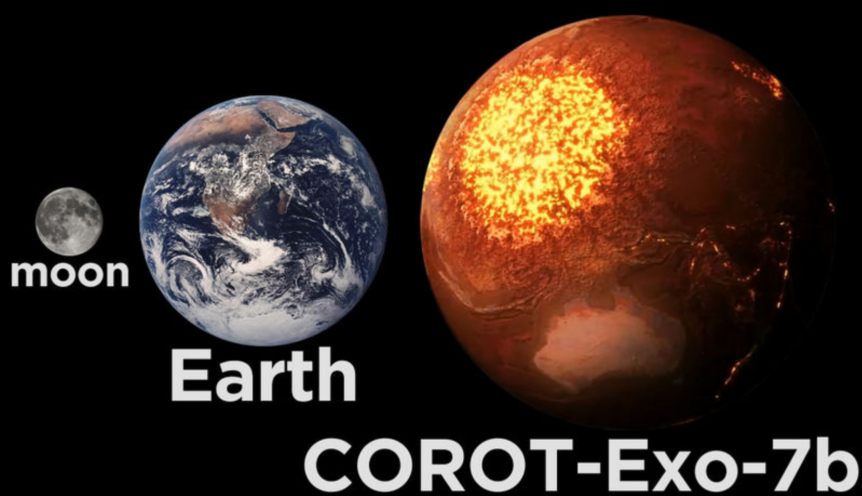


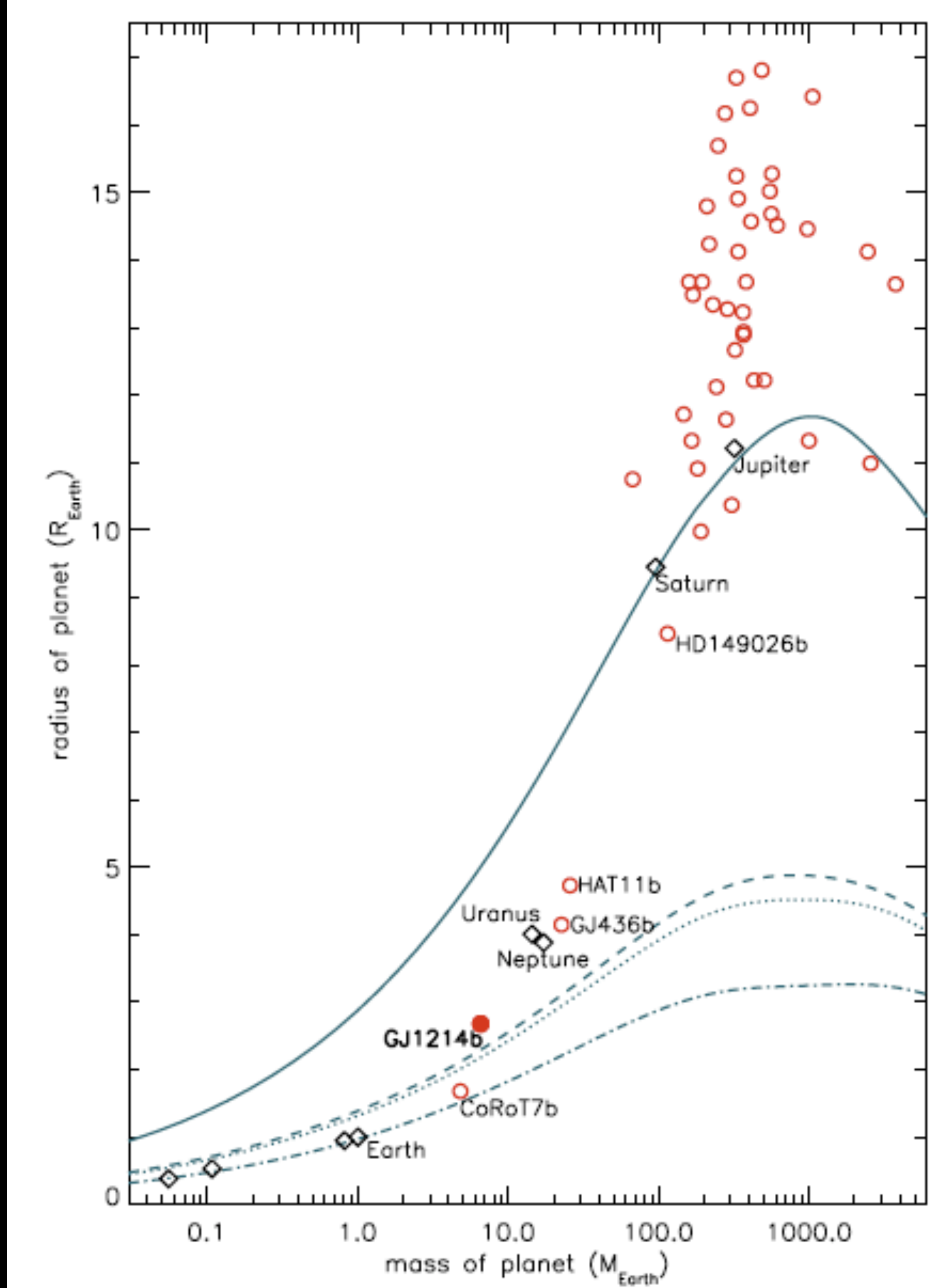
Not all small planets are rocky!



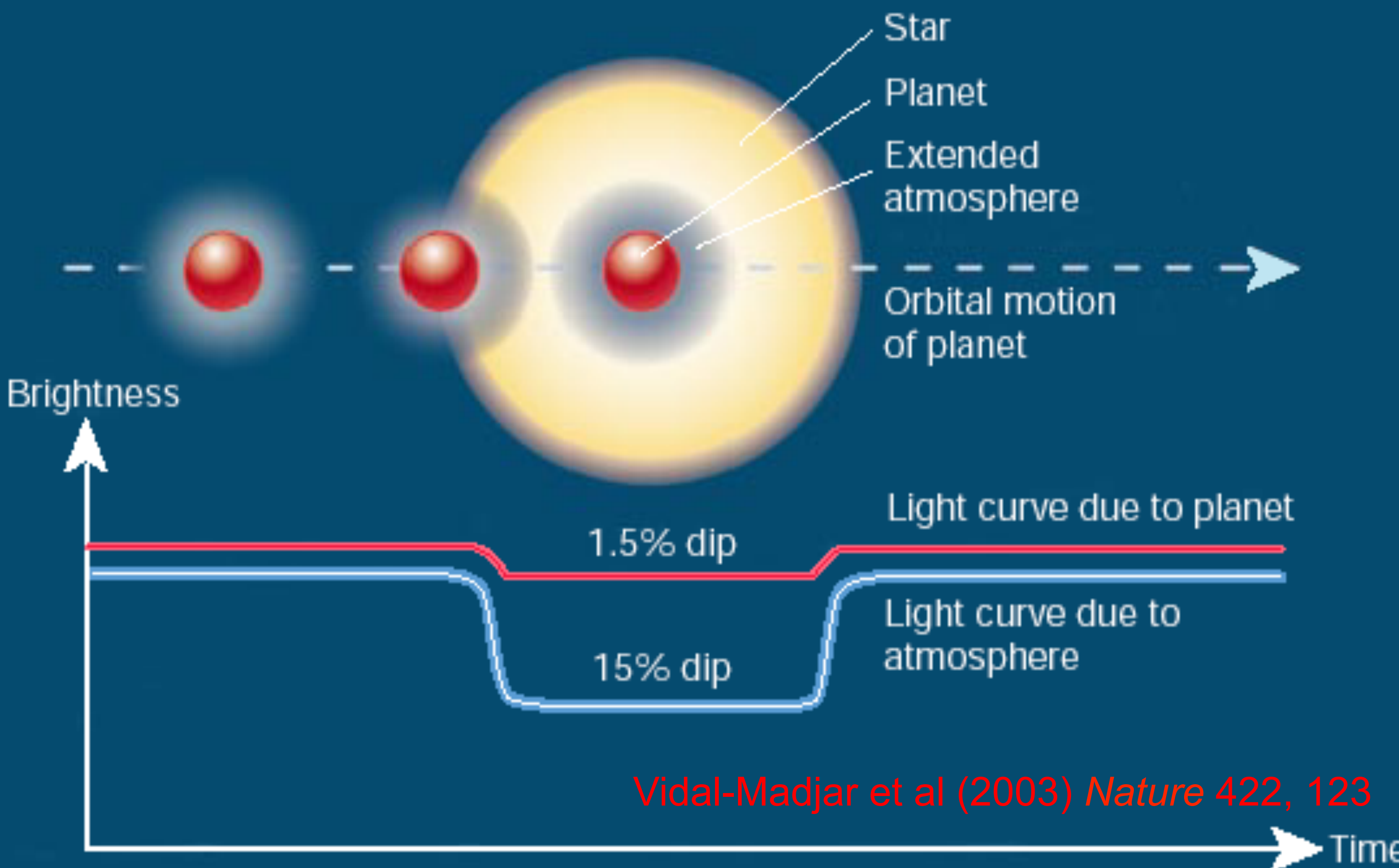
Densities

- Corot 7b
  - $4.8 M_{\oplus}$, $1.7\ R_{\oplus}$ 150pc
  - $\rho = 5.6\ g\ cm^{-3}$
  - $7.22 M_{\oplus}$ and $\sim 3.7 g\ cm^{-3}$
- GJ1214b
  - $6.6 M_{\oplus}$, $2.68\ R_{\oplus}$, 13pc.
  - $\rho = 1.87\ g\ cm^{-3}$





Transmission Spectroscopy



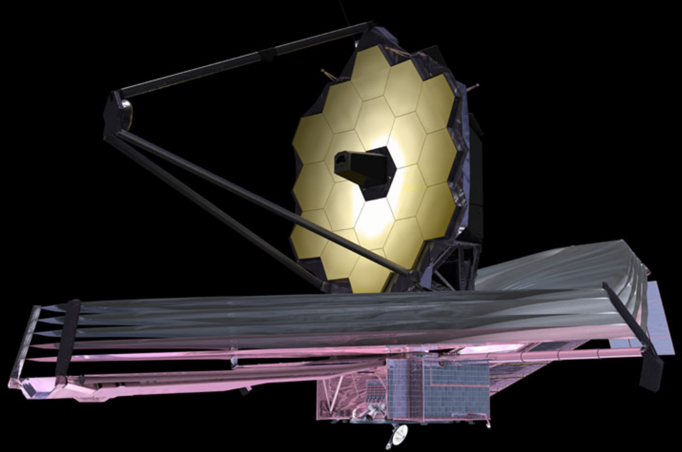
Vidal-Madjar et al (2003) *Nature* 422, 123

Atmospheric molecules, including biosignature gases, can be detected this way,

Transit Transmission Missions

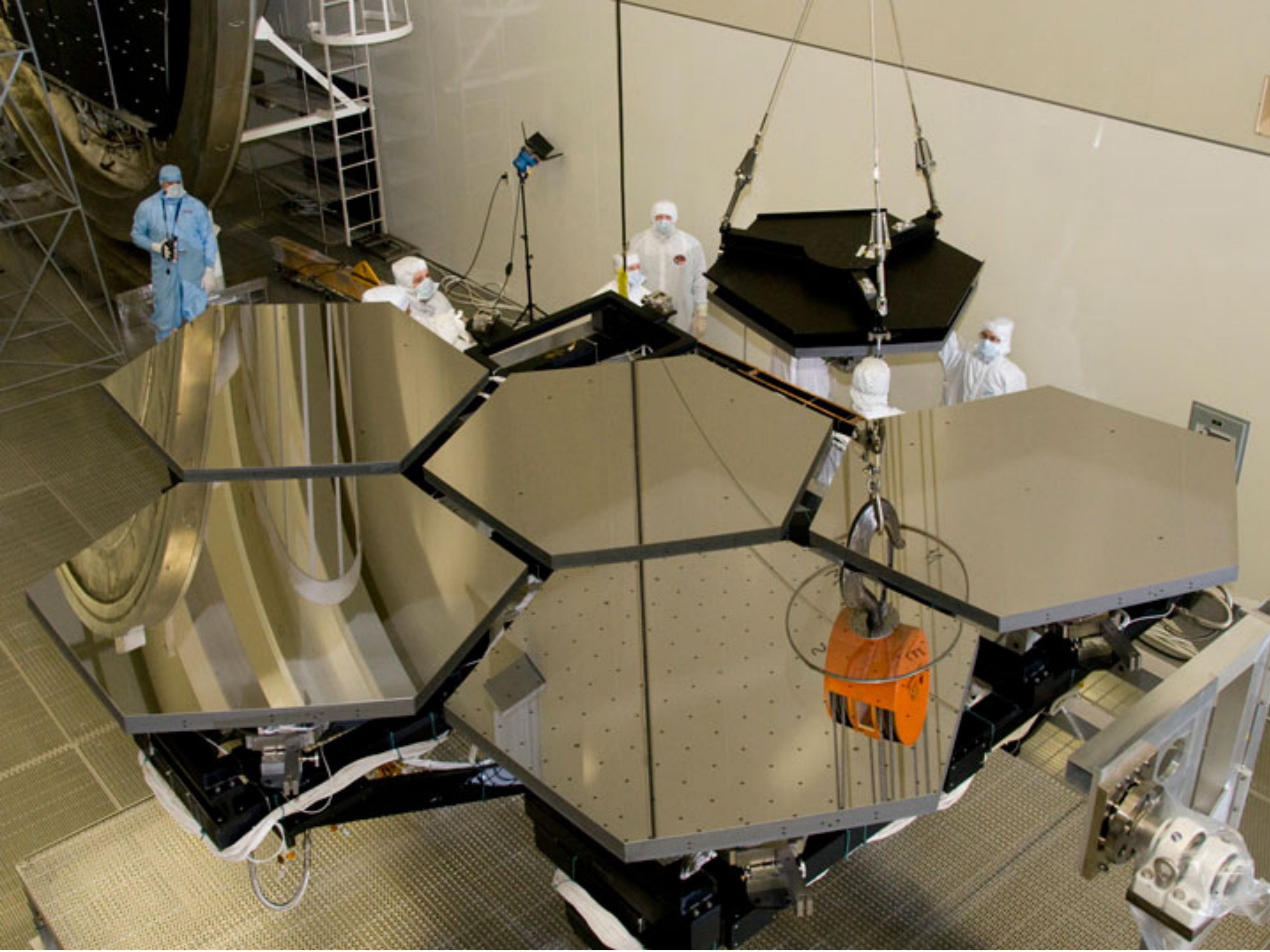
JWST

- Funded NASA mission
- 25m^2 mirror, Earth-Sun L2 orbit
- Instruments that cover 0.6-27μm
- Folded at launch (~2019)

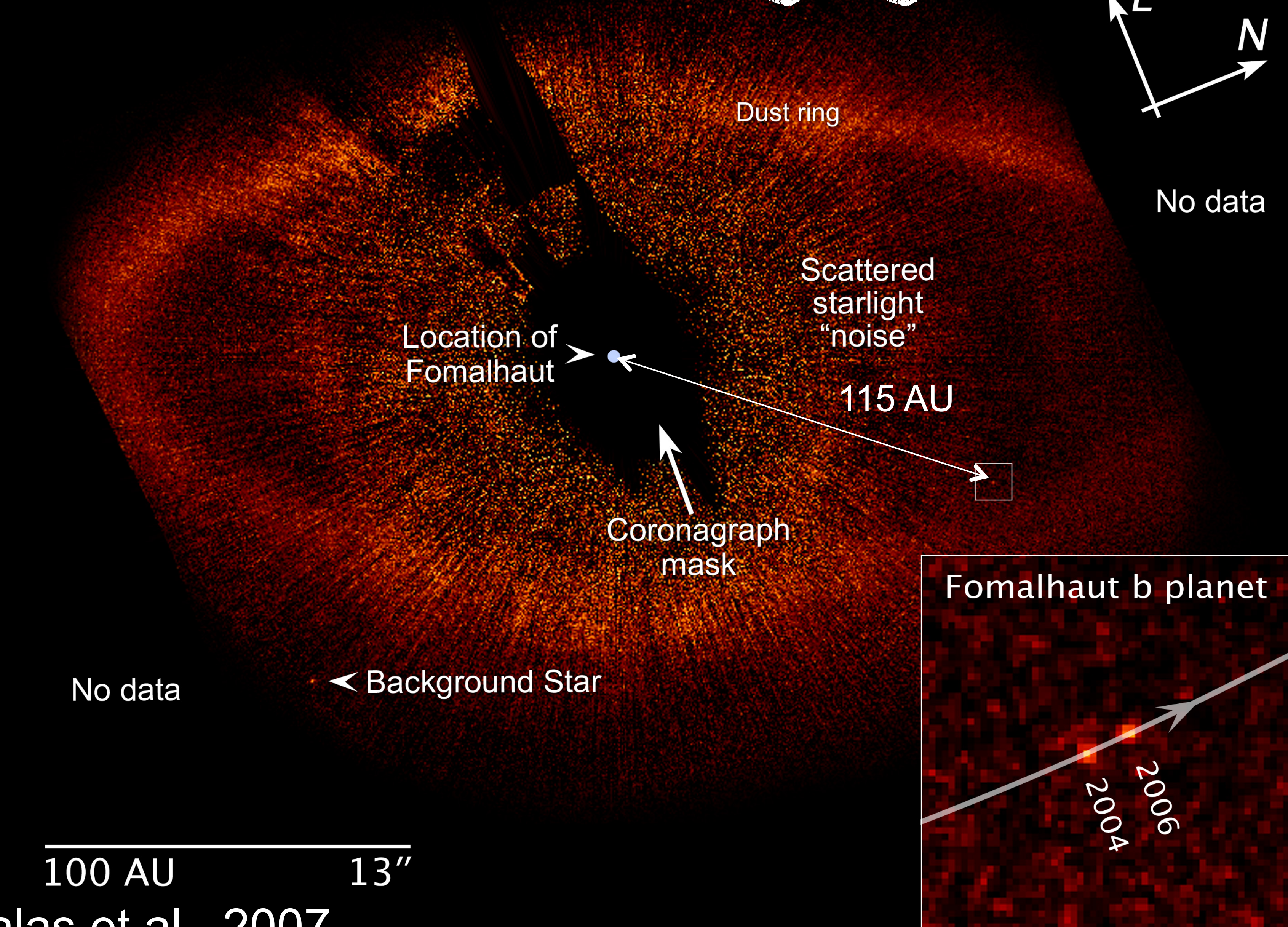


EChO

- ESA mission concept
- 1.1 m^2 mirror, L2 orbit
- 0.4-11μm
- Launch ~2020-2022

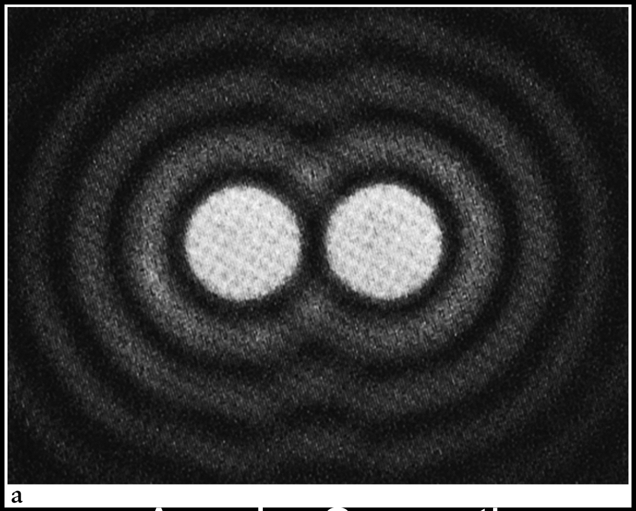


Direct Imaging

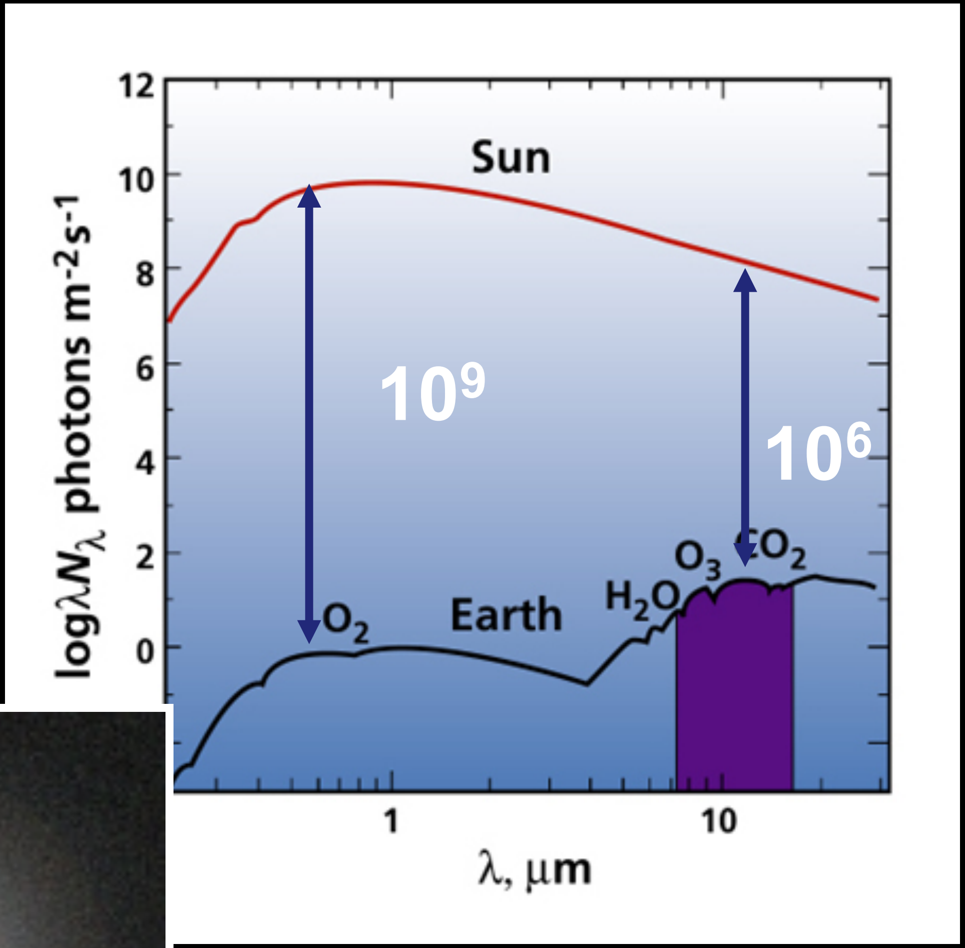


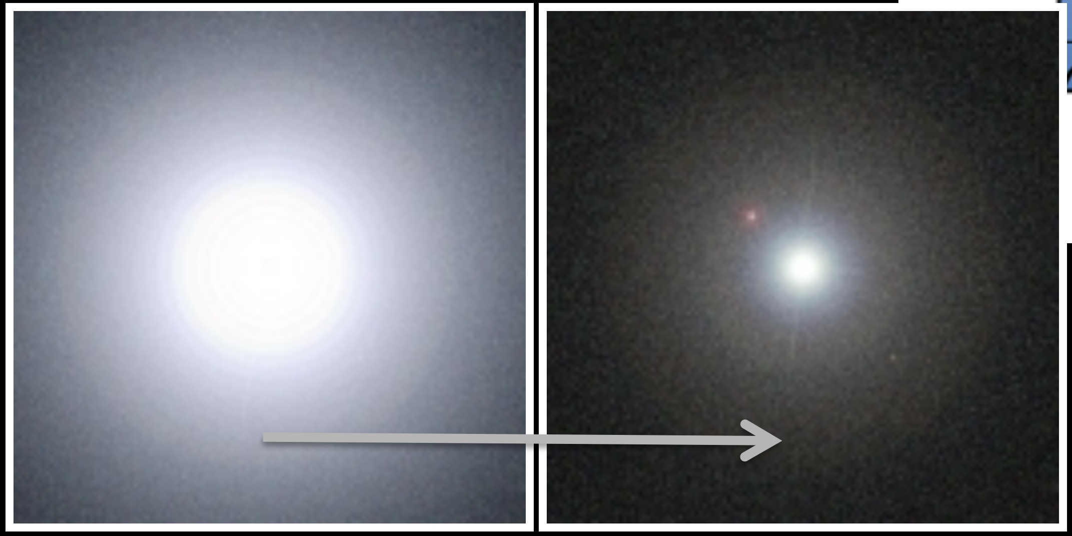
Kalas et al., 2007.

Challenges to Imaging the HZ



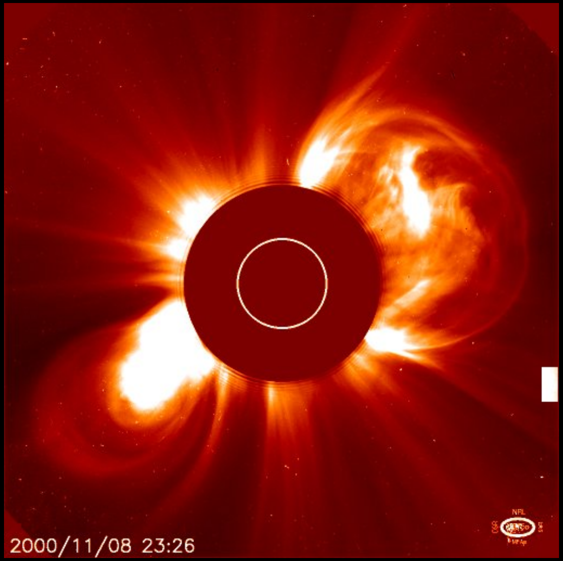
Angular Separation
θ=1.22 λ/D

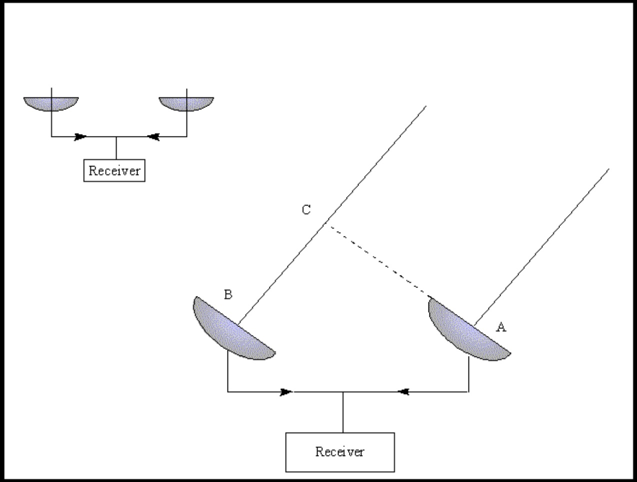


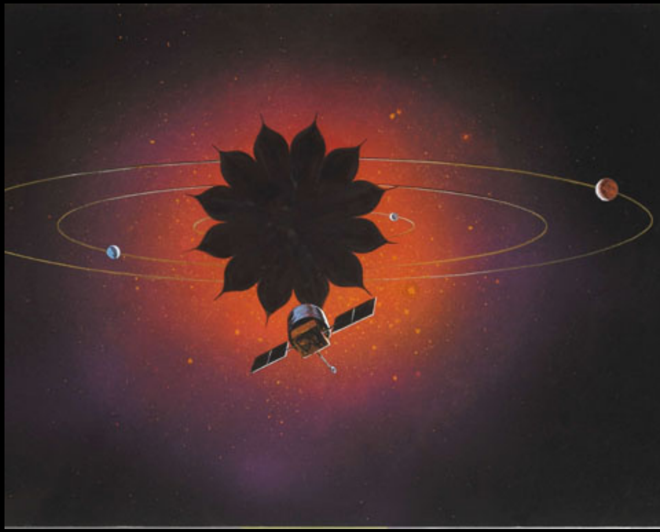


Starlight Suppression

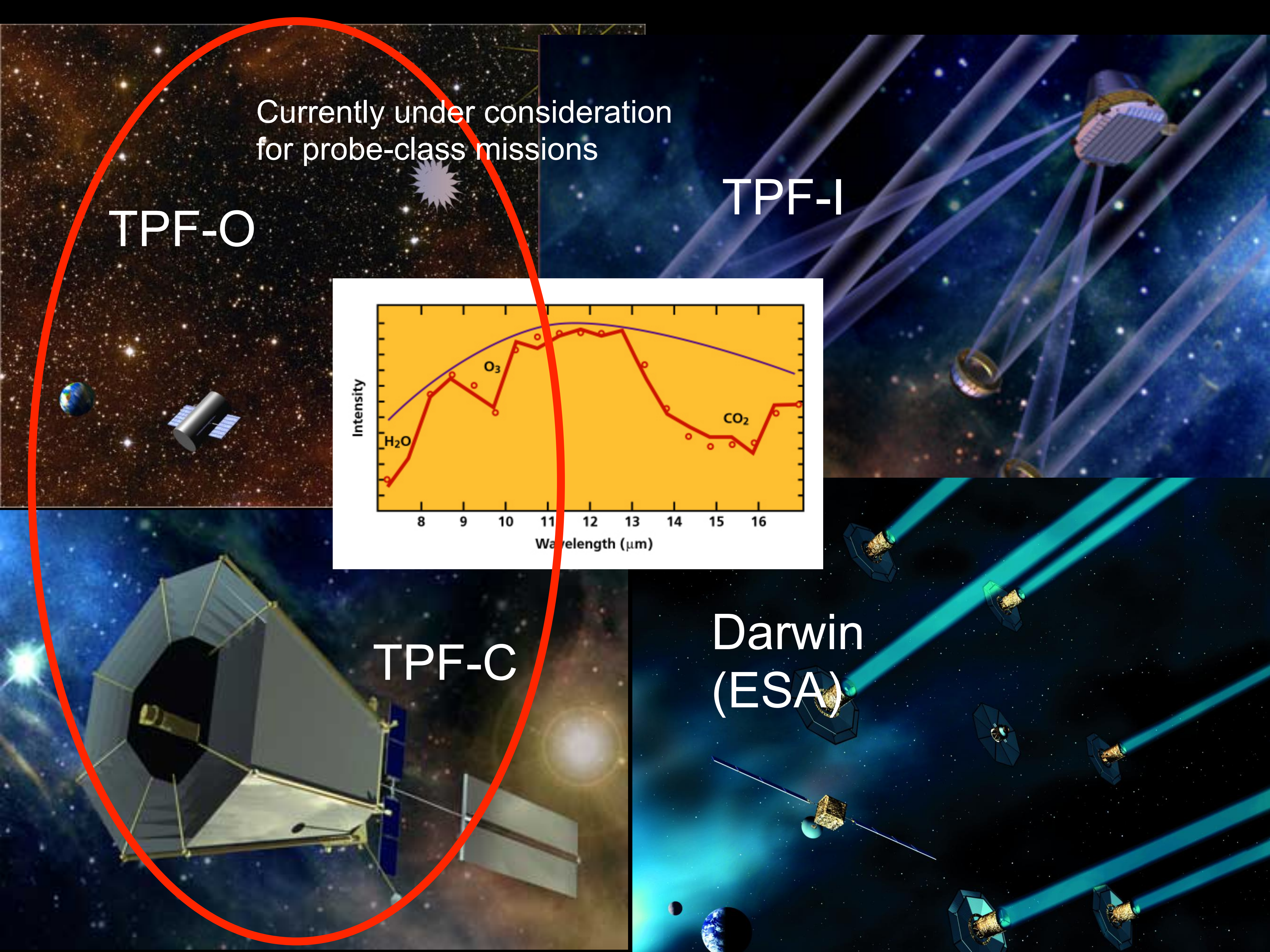
Three Approaches



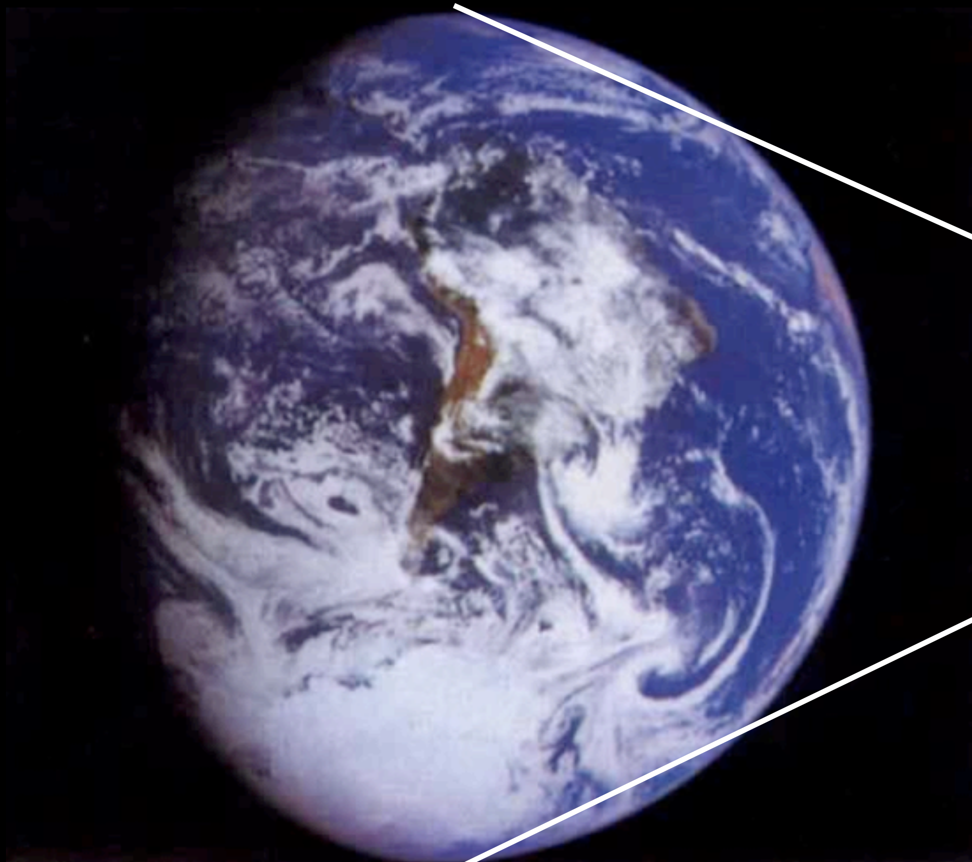




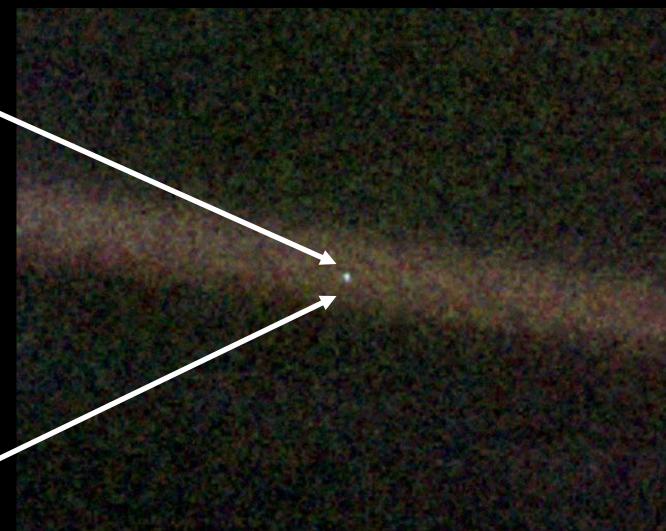
Coronograph Interferometer Occulter


Currently under consideration
for probe-class missions
TPF-O
TPF-I
TPF-C
Darwin
(ESA)
Intensity
H2O
O3
CO2
8
9
10
11
12
13
14
15
16
Wavelength (μm)

Challenges to Characterization



NASA/Galileo



NASA/Voyager 1

Detecting Biosignatures on Extrasolar Planets

- We will have no direct spatial information.
- Measurement limits sampling to:
  - Planetary near-surface to upper atmosphere (Transmission)
  - Or “disk-averaged”! (Direct Imaging)
- The signs of habitability and life must be a global and interacting strongly with the atmosphere
  - Productivity = detectability, and favors a surface biosphere.

How can we tell if a planet is inhabited?

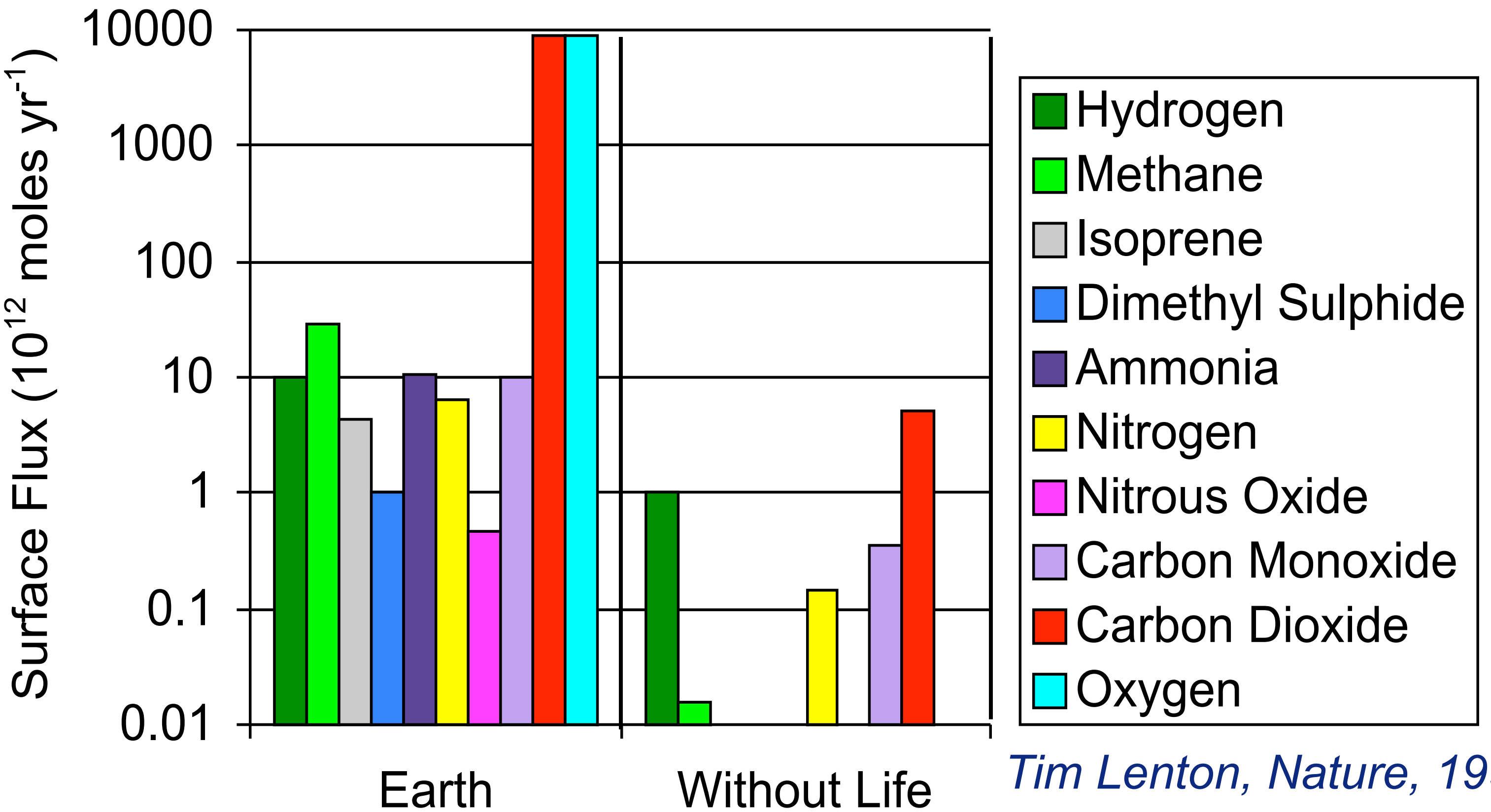
Without direct contact with an alien civilization, or traveling to the nearest planetary system, our best chance for finding life in the Universe is to look for *global changes* in the atmosphere and surface of a terrestrial planet.

Distant Signs of Life

- *Astronomical Biosignatures* are global-scale photometric, spectral or temporal features indicative of life.
- Earth shows us that life can provide global-scale modification of:
  - A planet's atmosphere
  - A planet's surface
  - A planet's appearance over time
- Biosignatures must always be identified in the context of the planetary environment
  - e.g. Earth methane and Titan methane
- False positives and "anti-biosignatures" may exist.


Atmospheric Biosignatures

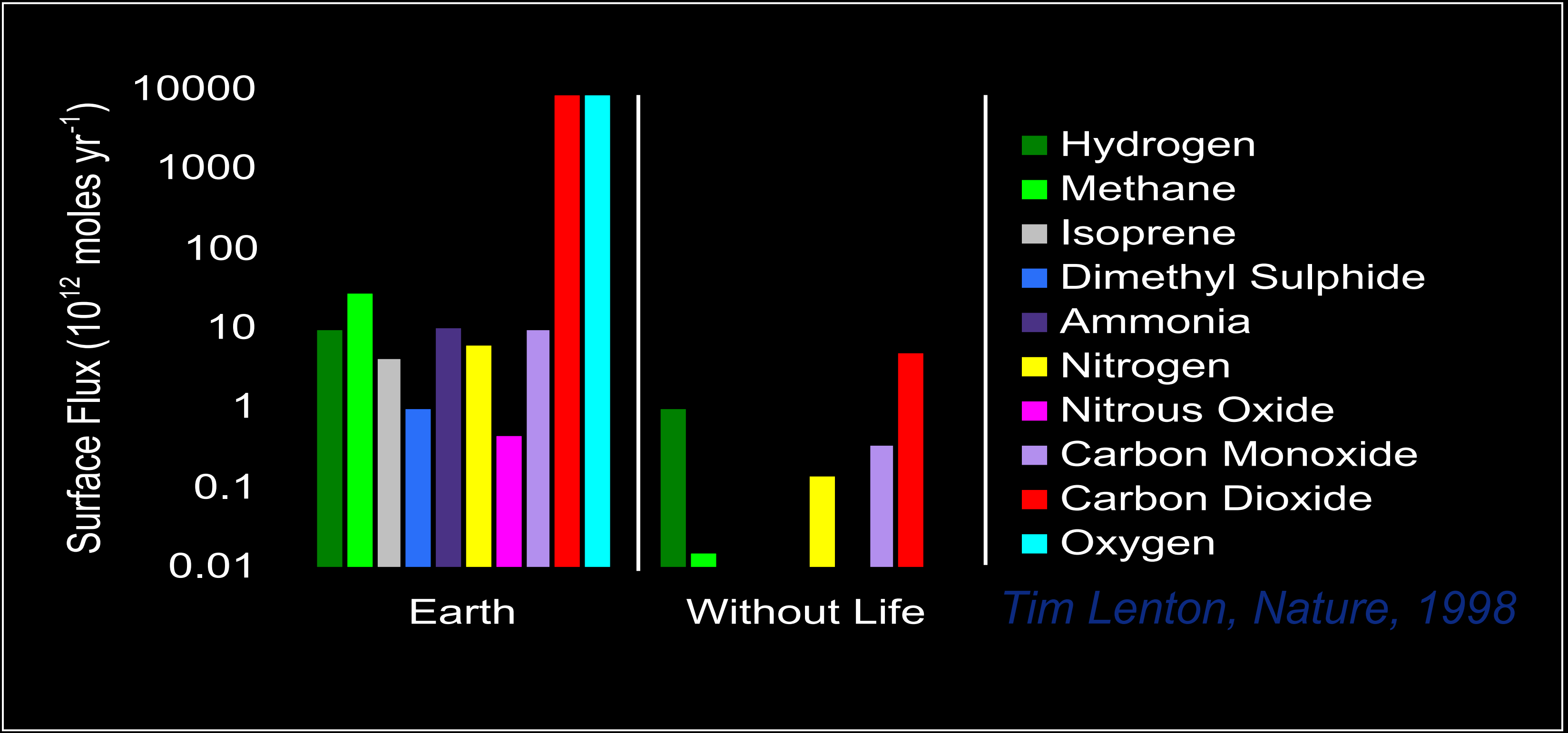
Biological Modification of the Atmosphere



Tim Lenton, Nature, 1998

- Life modifies the atmosphere via production of gaseous by-products of metabolism (e.g. O_2 from photosynthesis).
- Because there is an active source, life's gases are often seen in the atmosphere in *chemical disequilibrium.*

Generating an Atmospheric Biosignature



- Biological Source
- Atmospheric Lifetime
- Spectral Features

Genus	T_{opt} (°C)	pH_{opt}	Principal energy-yielding reactions
Crenarchaeota			
Thermofilum	88	5.5	Organic compound + $S^0 \rightarrow H_2S + CO_2$
Thermoproteus	88	6	$H_2 + S^0 \rightarrow H_2S$
			Organic compound + $S^\circ \rightarrow H_2S + CO_2$
Pyrodictium	105	6	$H_2 + S^0 \rightarrow H_2S$
			$H_2 + 2\ Fe^{3+} \rightarrow 2\ Fe^{3+} + 2\ H^+$
			Organic compound $\rightarrow CO_2 + H_2$ + fatty acids
Pyrolobus	106	5.5	$4\ H_2 + S_2O_3^{2-} + 2H^+ \rightarrow 2\ H_2S + 3\ H_2O$
			$4\ H_2 + NO_3^- + H^+ \rightarrow NH_4^+ + 2\ H_2O + OH^-$
			$2\ H_2 + O_2$ [low concentration] $\rightarrow 2\ H_2O$
Pyrobaculum	100	6	$H_2 + S^0 \rightarrow H_2S$
			$H_2 + 2\ Fe^{3+} \rightarrow 2\ Fe^{2+} + 2\ H^+$
			$H_2 + NO_3^- \rightarrow NO_2^- + H_2O$
			Organic compound + $S^\circ \rightarrow H_2S$
			$2\ H_2 + O_2 \rightarrow 2\ H_2O$
Desulfurococcus	85	6	Organic compound + $S^0 \rightarrow H_2S + CO_2$
Stygiolobus	80	3	$H_2 + S^0 \rightarrow H_2S$
Acidianus	88	2	$H_2 + S^0 \rightarrow H_2S$
			$2\ S^0 + 3\ O_2 + 2\ H_2O \rightarrow 2\ H_2SO_4$
			$2\ H_2 + O_2 \rightarrow 2\ H_2O$
			$2\ FeS_2 + 7\ O_2 + 2\ H_2O \rightarrow 2\ FeSO_4 + 2\ H_2SO_4$
Sulfolobus	75	2–3	$2\ S^0 + 3\ O_2 + 2\ H_2O \rightarrow 2\ H_2SO_4$
			$2\ H_2 + O_2 \rightarrow 2\ H_2O$
			$2\ FeS_2 + 7\ O_2 + 2\ H_2O \rightarrow 2\ FeSO_4 + 2\ H_2SO_4$
			Organic compound + $O_2 \rightarrow H_2O + CO_2$
Euryarchaeota			
Methanopyrus	100		$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$
Thermococcus	88		Organic compound + $S^0 \rightarrow H_2S + CO_2$
Pyrococcus	100		Organic compound + $S^0 \rightarrow H_2S + CO_2$
			$H_3CCOCOO^- \rightarrow CO_2 + H_2 + H_3CCOO^-$
Methanothermus	83–88		$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$
			$H_2 + S^0 \rightarrow H_2S$
Methanobacterium	60–70	7–8	$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$
			$4\ HCOOH \rightarrow 3\ CO_2 + CH_4 + 2\ H_2O$
Methanococcus	65–88	6–7	$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$
			$4\ HCOOH \rightarrow 3\ CO_2 + CH_4 + 2\ H_2O$
Thermoplasma	55	2	Organic compound + $S^0 \rightarrow H_2S + CO_2$
			Organic compound + $O_2 \rightarrow H_2O + CO_2$
Archaeoglobus	83	7	$4\ H_2 + SO_4^{2-} + 2\ H^+ \rightarrow 4\ H_2O + H_2S$
			Organic compound + $SO_4^{2-} \rightarrow H_2S + CO_2$
			$H_2 + 2\ Fe^{3+} \rightarrow 2\ Fe^{2+} + 2\ H^+$
			$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$ [weak]
Ferroglobus	85	7	$2\ FeCO_3 + NO_3^- + 6\ H_2O \rightarrow 2\ Fe_3(OH)_3 + NO_2^- + 2\ HCO_3^- + 2\ H^+ + H_2O$
			$H_2 + NO_3^- \rightarrow NO_2^- + H_2O$
			$H_2S + NO_3^- \rightarrow NO_2^- + S^0 + H_2O$
Bacteria			
Aquifex	85		$H_2 + NO_3^- \rightarrow NO_2^- + H_2O$
			$2\ H_2 + O_2$ [low concentration] $\rightarrow 2\ H_2O$
			$2\ S^0 + 3\ O_2 + 2\ H_2O \rightarrow 2\ H_2SO_4$
Thermodesulfobacterium	70		Organic compound + $SO_4^{2-} \rightarrow H_2S + CO_2$
Thermotoga	80		Fermentation

Most entries are from Madigan *et al.* (2000). Supplementary information on methanogens is from Whitman *et al.* (1992) and Mueller *et al.* (1993).

Pilcher, 2003

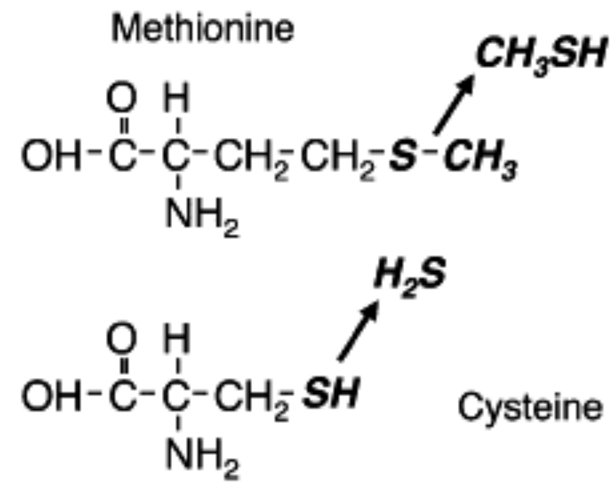
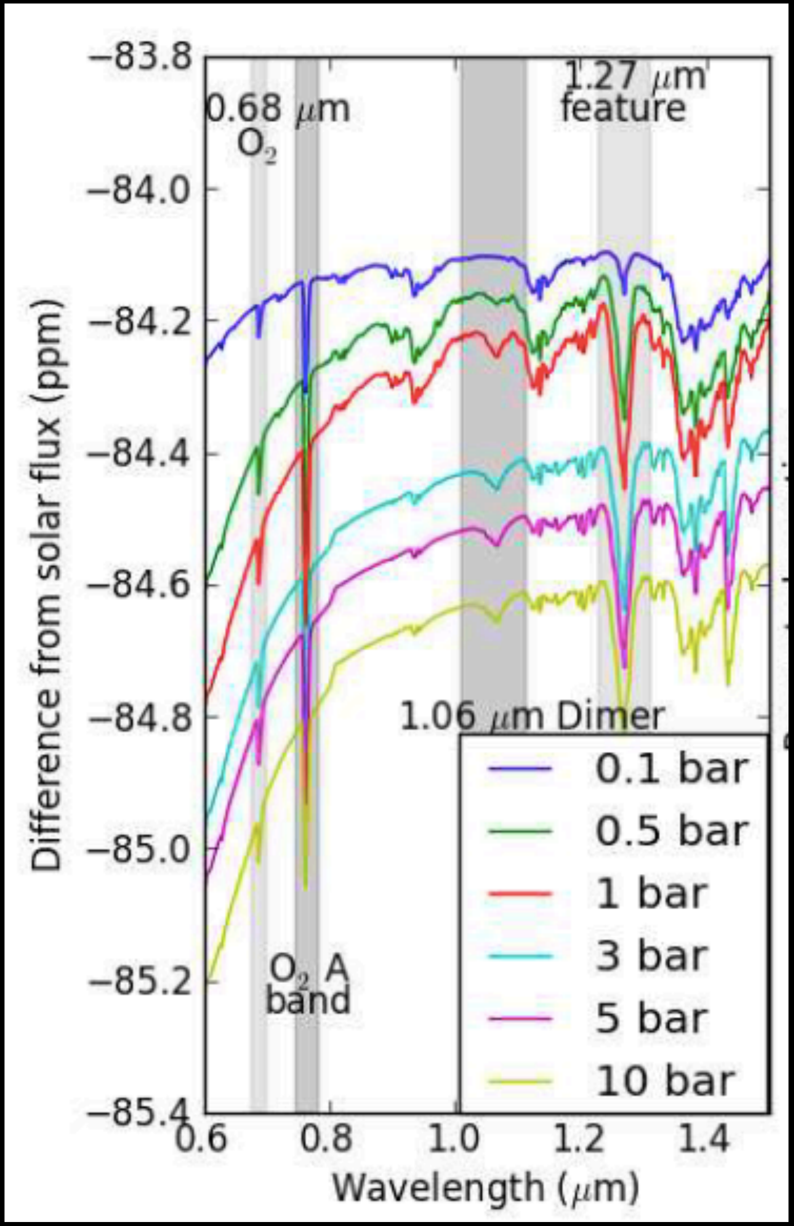


FIG. 5. The structures of the amino acids cysteine and methionine. Methionine contains a methio group ($-SCH_3$), which, when cleaved from the molecule and combined with hydrogen, forms methanethiol (CH_3SH). In contrast, when the sulfhydryl ($-SH$) group of cysteine is cleaved and combined with hydrogen, it forms hydrogen sulfide (H_2S).

But remember….

Productivity = Detectability

Oxygen in Transit Transmission

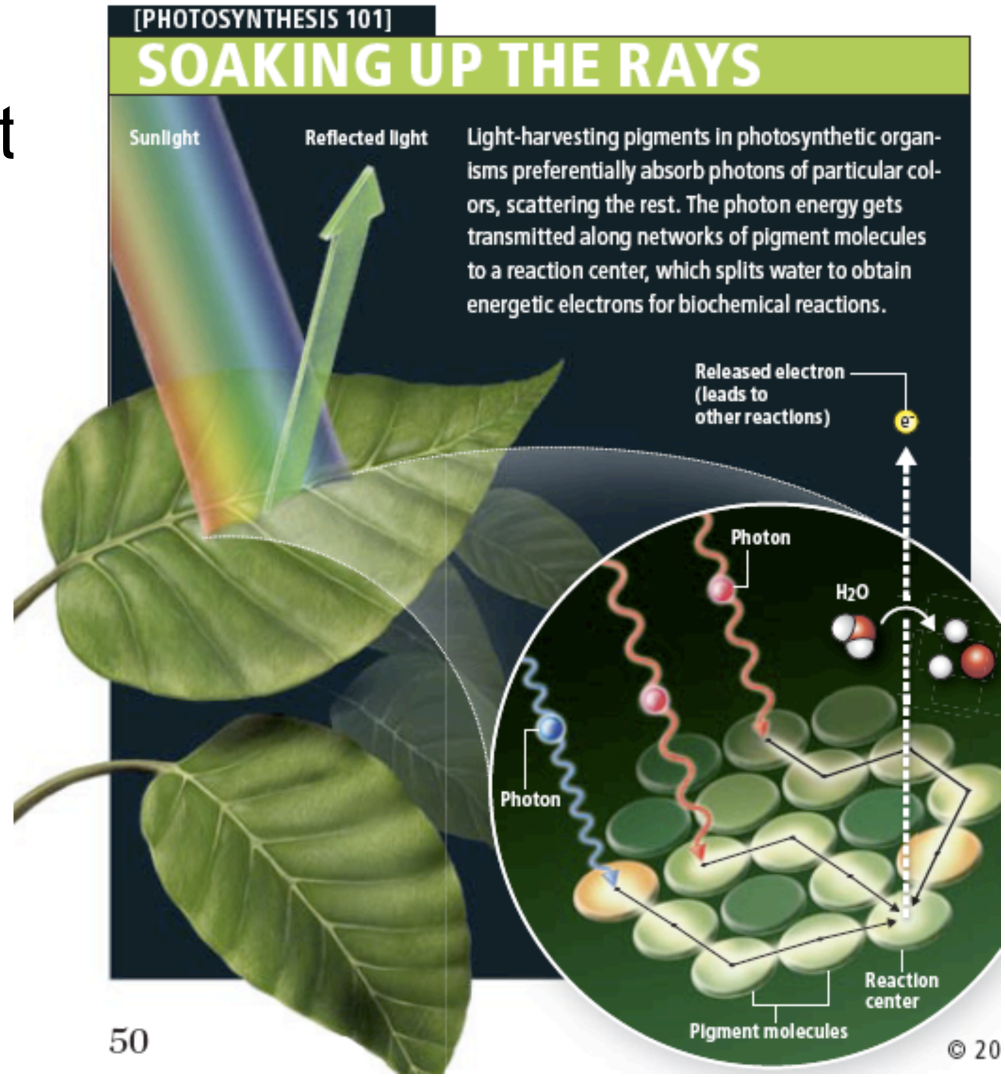


Misra, Meadows, Claire and Crisp, *Astrobiology*, in review

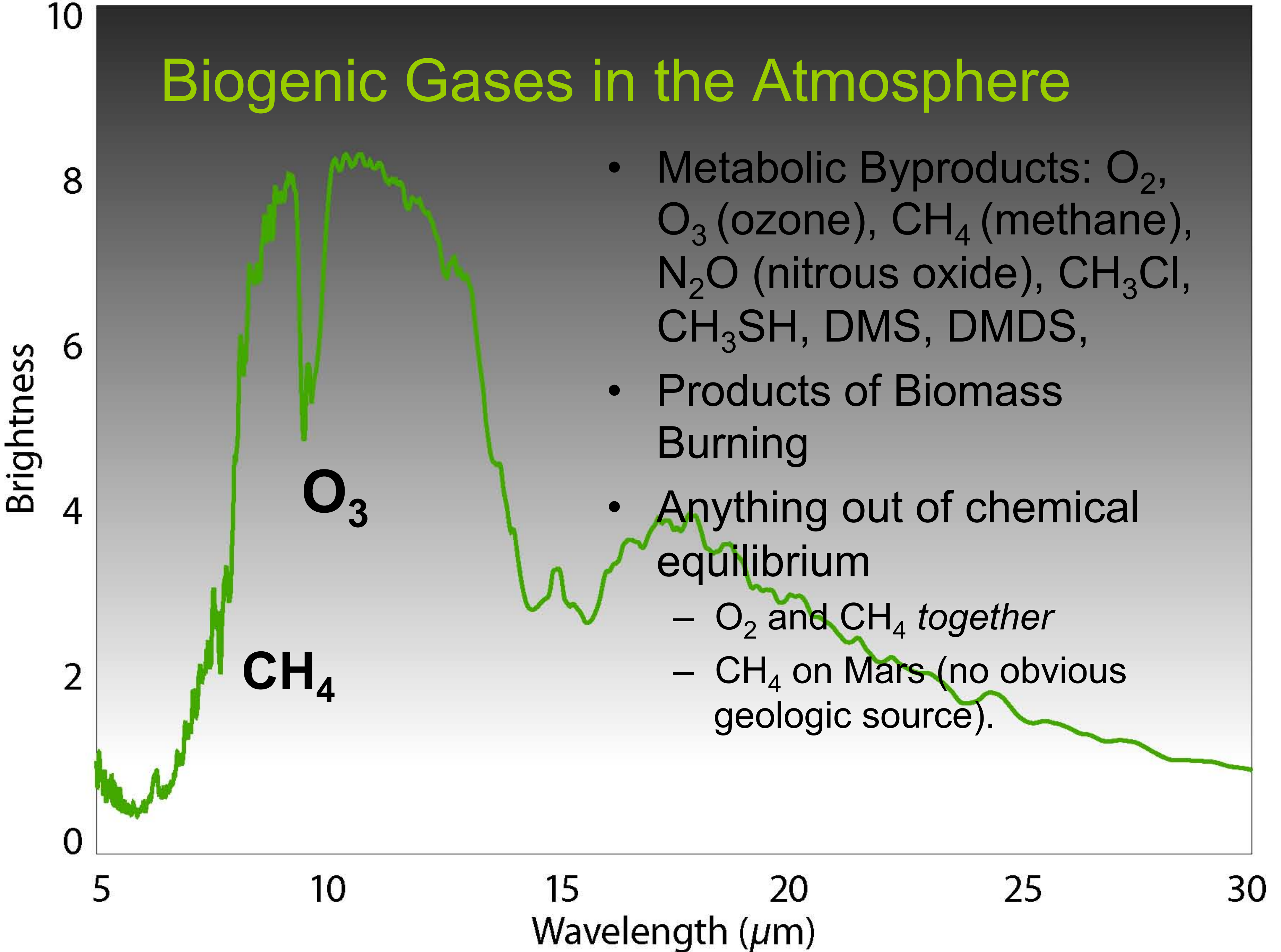
Photosynthesis:
The Ultimate Life Process?

- Photosynthesis is so successful on this planet that it is now the foundation for almost all life.

- Assumption: It is highly likely that habitable planets ultimately develop photosynthesis.



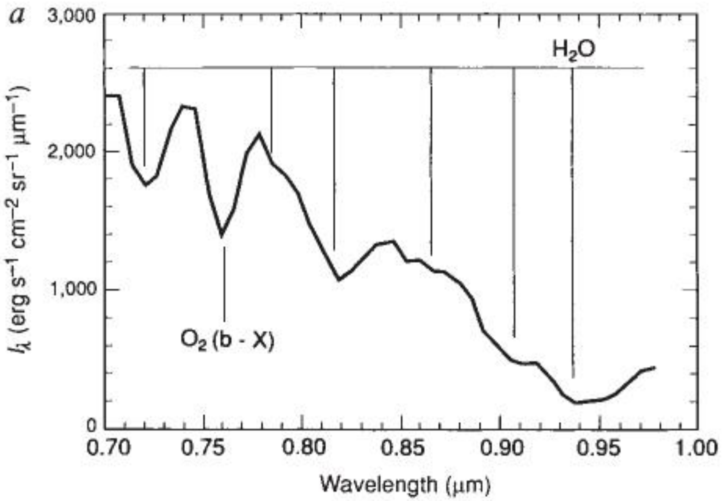
Biogenic Gases in the Atmosphere



- Metabolic Byproducts: O_2, O_3 (ozone), CH_4 (methane), N_2O (nitrous oxide), CH_3Cl, CH_3SH, DMS, DMDS,
- Products of Biomass Burning
- Anything out of chemical equilibrium
  - O_2 and CH_4 *together*
  - CH_4 on Mars (no obvious geologic source).

Detecting Life on Earth: The *Galileo* Flyby.

- Galileo observed the Earth's biosignatures from space at relatively low spectral resolution (~100) during a flyby on its way to Jupiter. (Sagan et al., 1993).



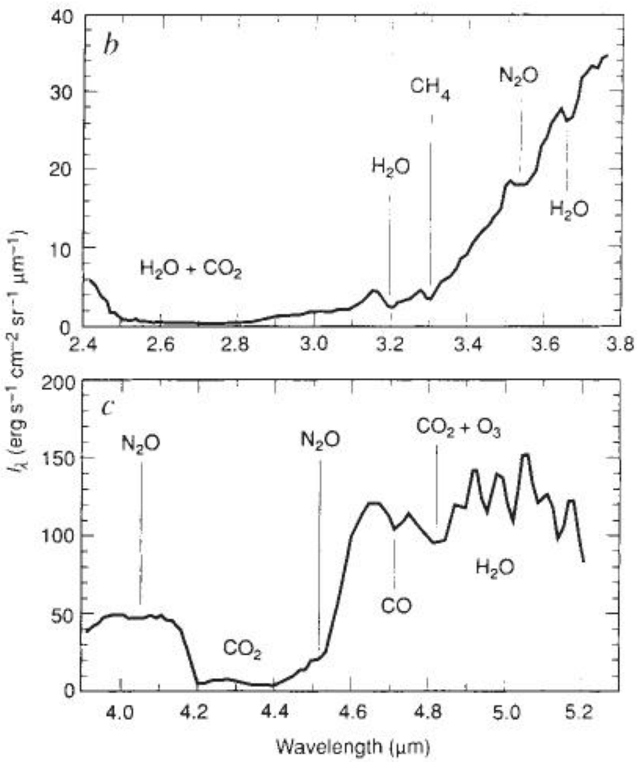


FIG. 1 *a*, Galileo long-wavelength-visible and near-infrared spectra of the Earth over a relatively cloud-free region of the Pacific Ocean, north of Borneo. The incidence and emission angles are 77° and 57° respectively. The ($b'\sum_g^+ - X^3\sum_g^-$) 0–0 band of O_2 at 0.76 μm is evident, along with a number of H_2O features. Using several cloud-free regions of varying airmass, we estimate an O_2 vertical column density of 1.5 km-amagat ± 25%. *b* and *c*, Infrared spectra of the Earth in the 2.4–5.2 μm region. The strong υ_3 CO_2 band is seen at the 4.3 μm, and water vapour bands are found, but not indicated, in the 3.0 μm region. The υ_3 band of nitrous oxide, N_2O, is apparent at the edge of the CO_2 band near 4.5 μm, and N_2O combination bands are also seen near 4.0 μm. The methane (0010) vibrational transition is evident at 3.31 μm. A crude estimate[10] of the CH_4 and N_2O column abundances is, for both species, of the order of 1 cm-amagate (≡1 cm path at STP).

Detecting Life On Earth

TABLE 1 Constituents of the Earth's atmosphere (volume mixing ratios)

Molecule	Standard abundance (ground-truth Earth)	Galileo value*	Thermodynamic equilibrium value Estimate 1†	Thermodynamic equilibrium value Estimate 2‡
N_2	0.78		0.78	
O_2	0.21	0.19 ± 0.05	0.21§	
H_2O	0.03–0.001	0.01–0.001	0.03–0.001	
Ar	9×10^{-3}		9×10^{-3}	
CO_2	3.5×10^{-4}	$5 \pm 2.5 \times 10^{-4}$	3.5×10^{-4}	
CH_4	1.6×10^{-6}	$3 \pm 1.5 \times 10^{-6}$	$< 10^{-35}$	10^{-145}
N_2O	3×10^{-7}	$\sim 10^{-6}$	2×10^{-20}	2×10^{-19}
O_3	10^{-7}–10^{-8}	$> 10^{-8}$	6×10^{-32}	3×10^{-30}

* Galileo values for O_2, CH_4 and N_2O from NIMS data; O_3 estimate from UVS data.

† From ref. 16 (P, 1 bar; T, 280 K).

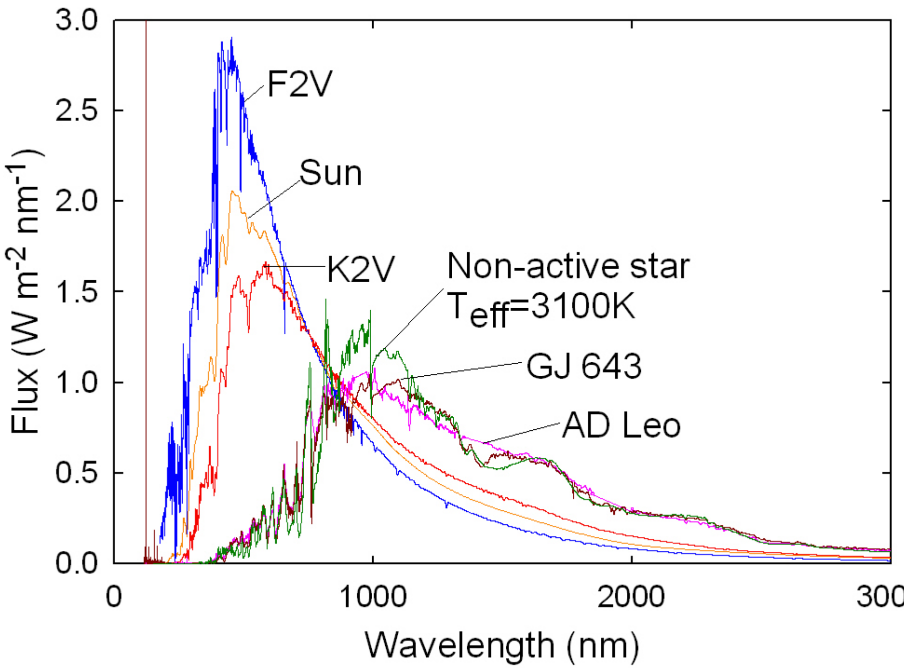
‡ From ref. 17 (P, 1 bar; T, 298 K).

§ The observed value; it is in thermodynamic equilibrium only if the under-oxidized state of the Earth's crust is neglected.

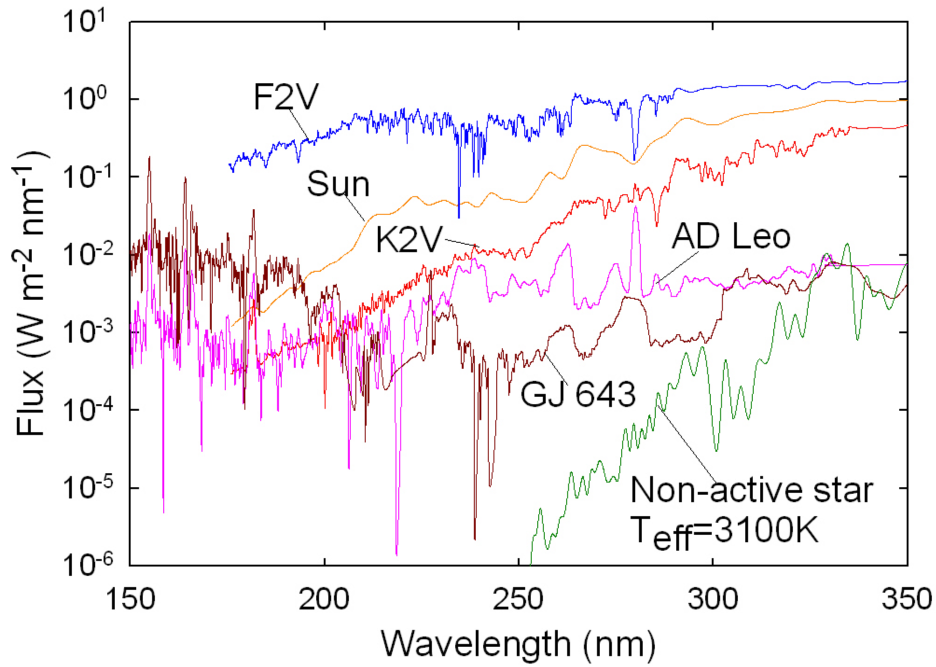
Sagan et al., 1993


Earths Around
Other Stars

Spectral "Type"

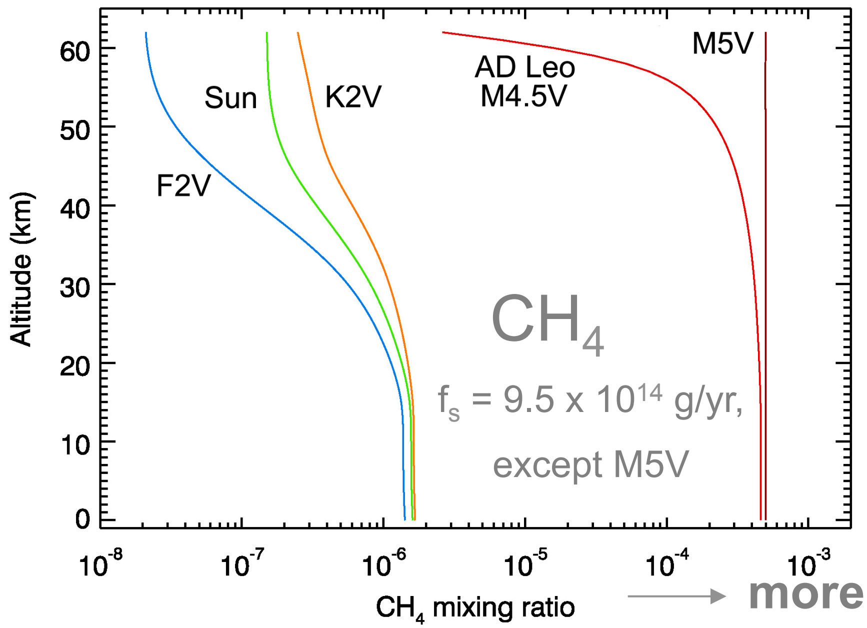


Visible

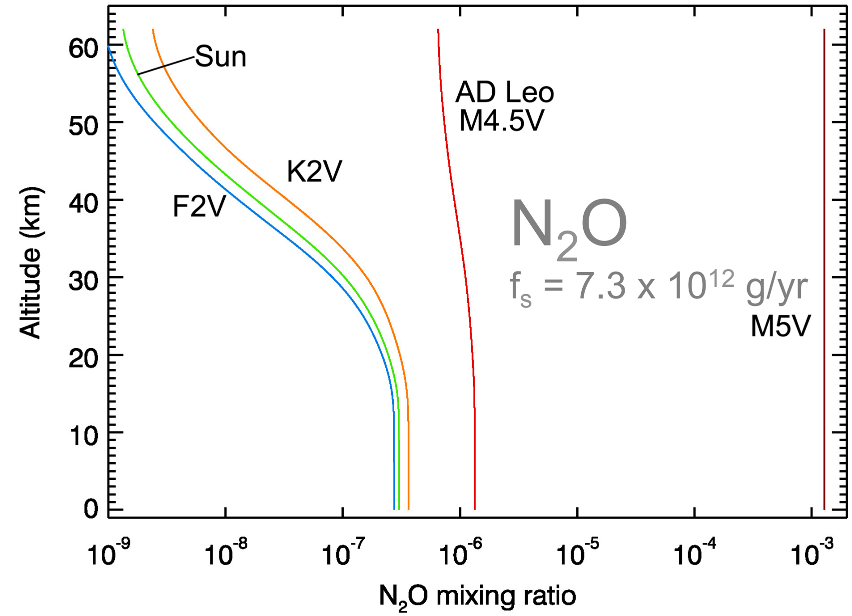


UV

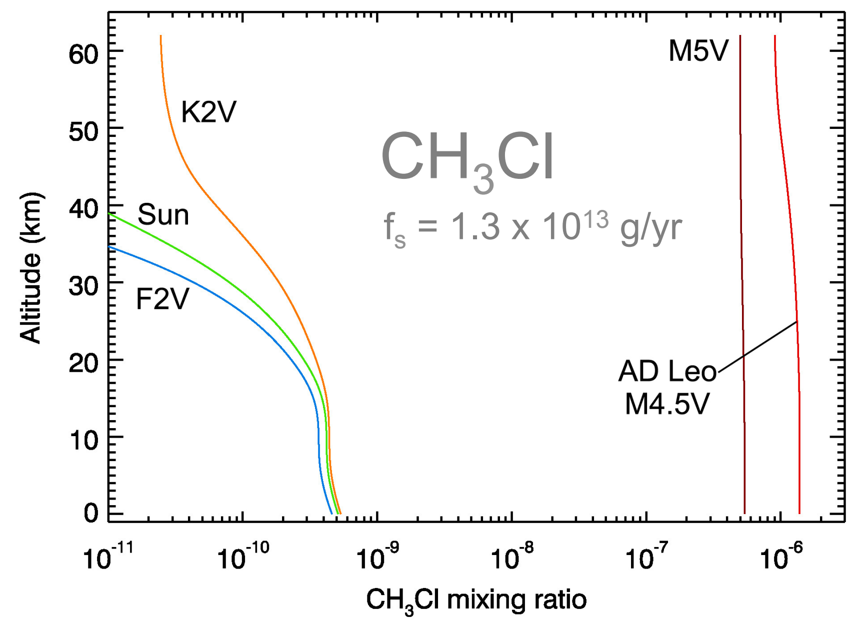
Enhancing Atmospheric Biosignatures



Segura et al., 2003, 2005



- Earth-like planets around cooler stars show enhanced biosignature abundances (Segura et al., 2003, 2005)
  - M stars less effective at O_3 photolysis.
- Enhancements in biosignatures, (including O_3), are *also* seen when an Earth-like planet is moved towards the outer edge of its habitable zone (Grenfell et al., 2006, 2007)

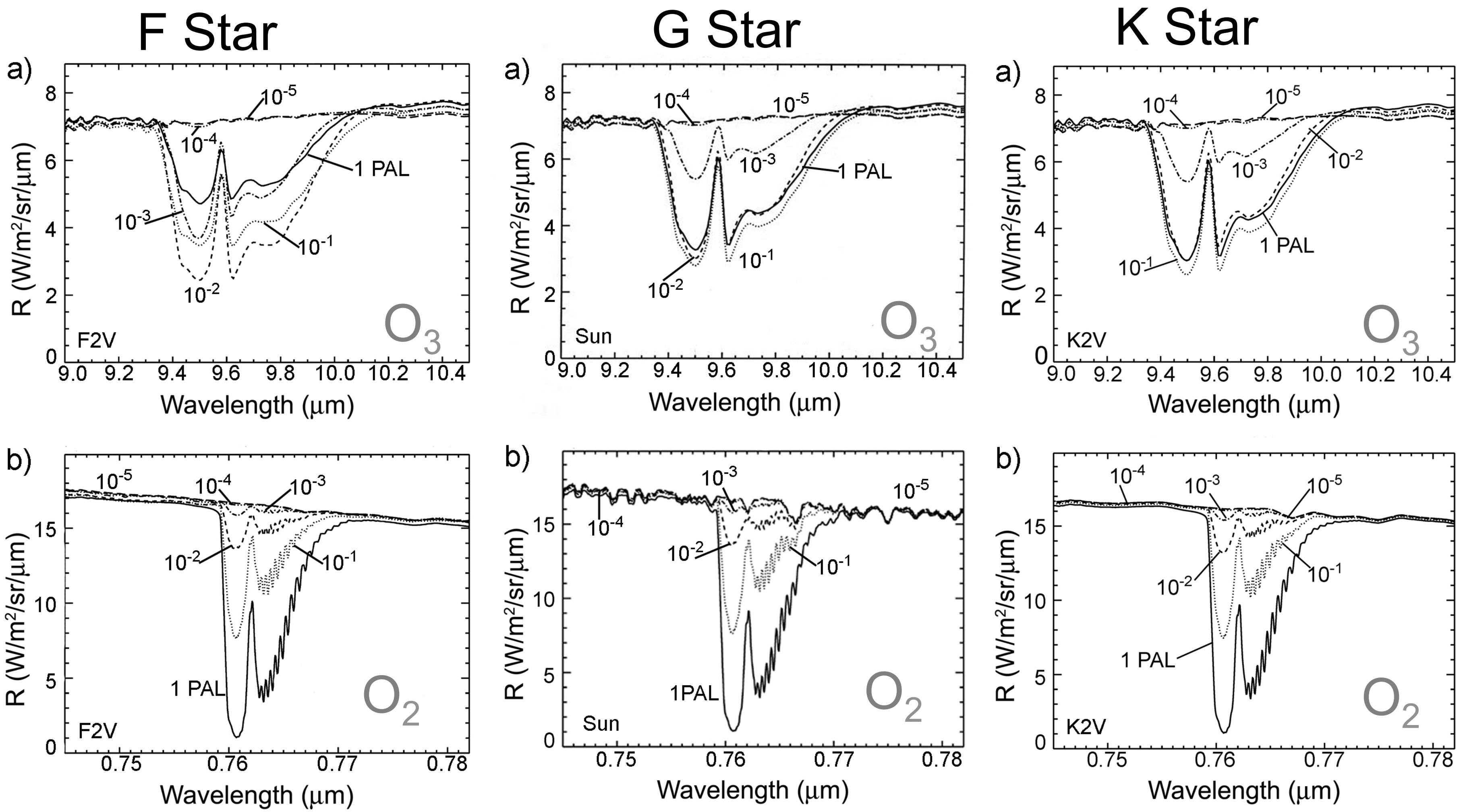


Biosignature Lifetimes

Parent star	Lifetime (yr)		
	CH_4	CH_3Cl	N_2O
Sun	4.4	0.6	2×10^2
F2V	3.9	0.5	1×10^2
K2V	15	2	3×10^2
M4.5V	1×10^3	2×10^3	7×10^2
M5V	6×10^3	6×10^3	7×10^5

- CH_4 and CH_3Cl have longer lifetimes on M star planets due to the spectral slope of the incoming UV, which is less effective at O_3 photolysis and the production of $O(^1D)$
- N_2O lifetime also increases, and is inversely proportional to the incident UV radiation from 100-220 nm.

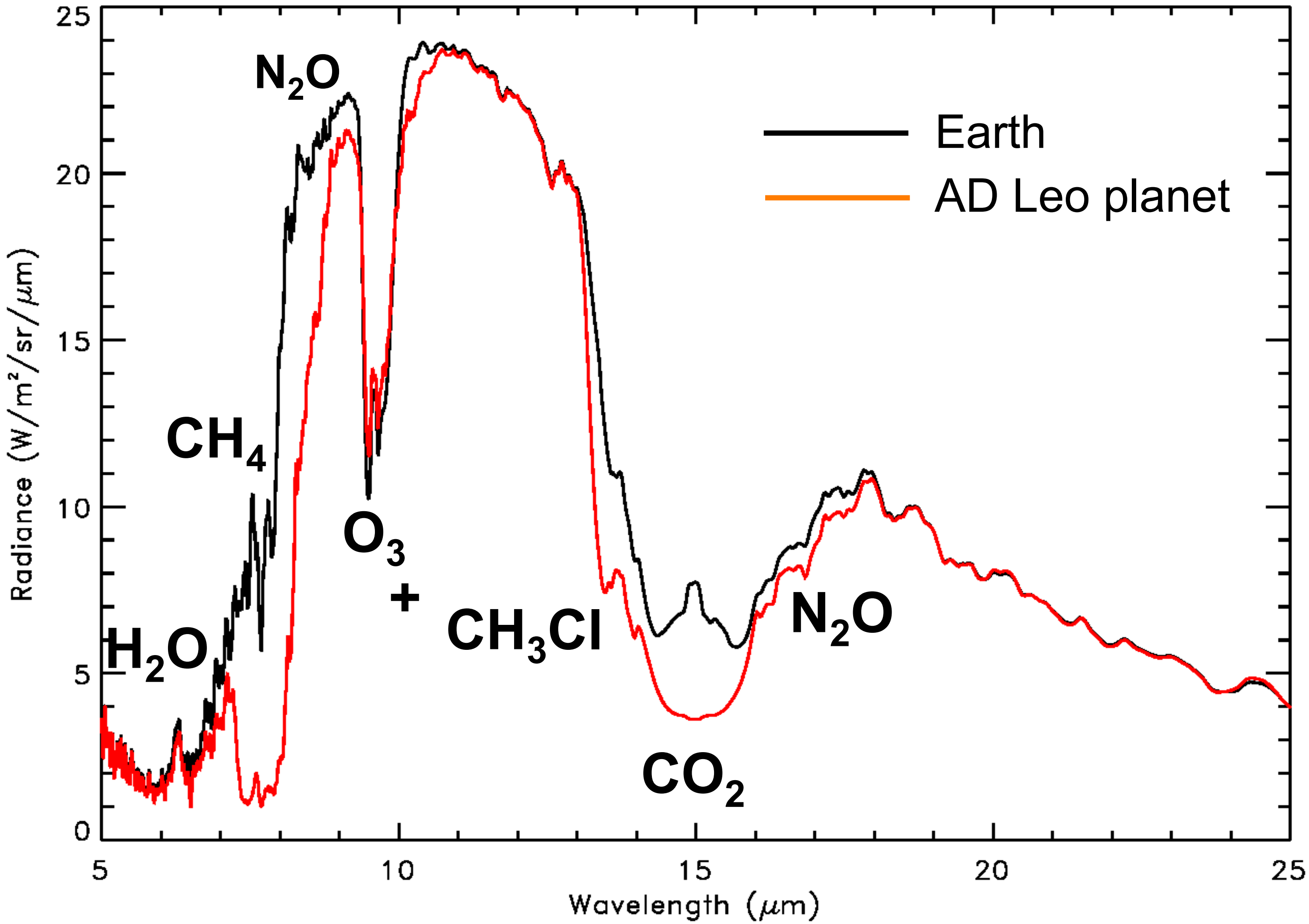
O_2 and O_3 Detectability vs O_2 Abundance



Earth-like planetary spectra at different O_2 abundances around different stars

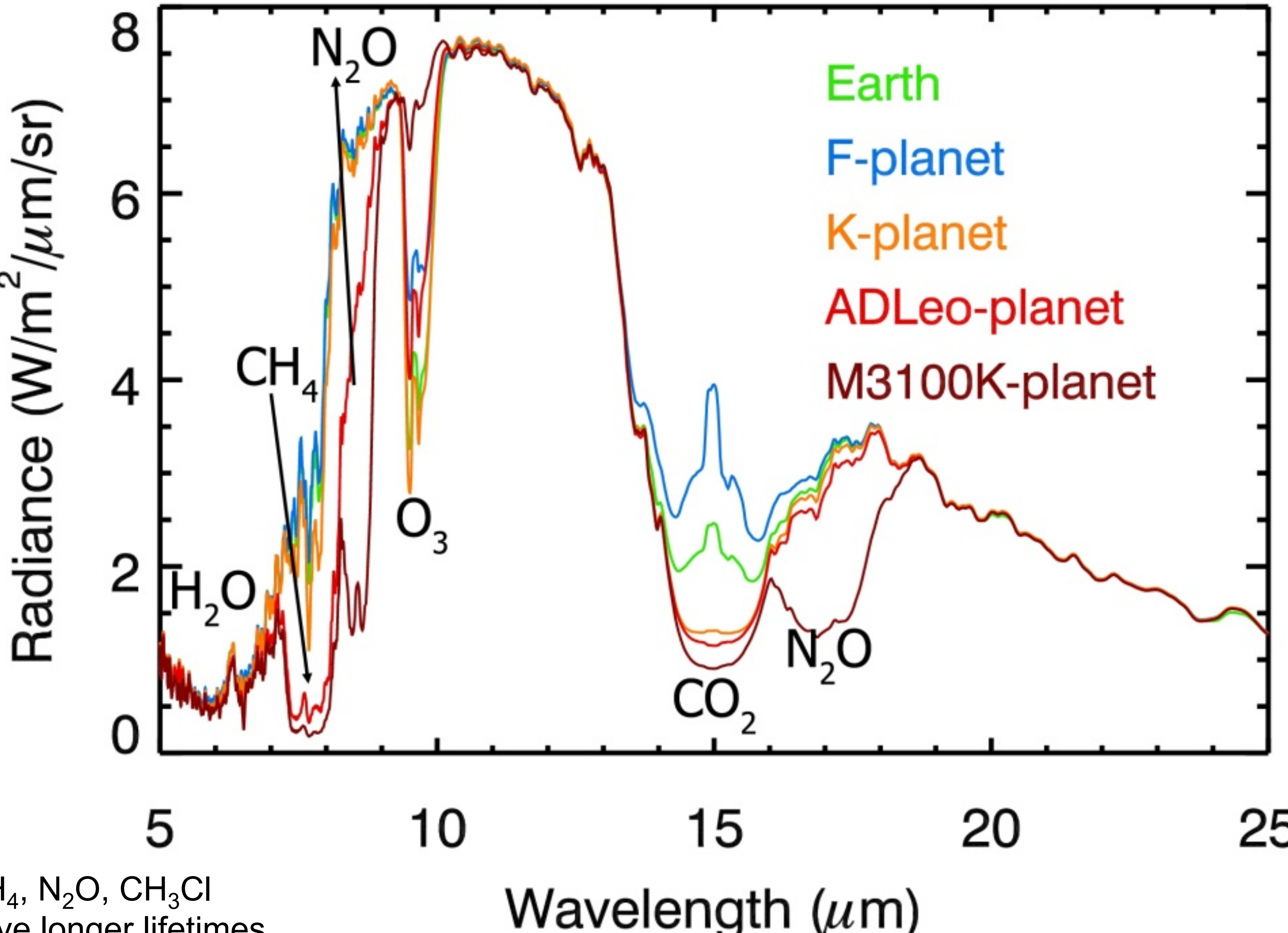
- look similar in the visible – O_2 most detectable at concentrations $\geq 10^{-2}$ PAL
- are similar in the MIR for G and K stars - O_3 most detectable down to 10^{-3} PAL of O_2
  - quite different for F stars, which are most sensitive to 10^{-1} – 10^{-2} PAL of O_2

Active M Star Planets



Earth-like planets around M stars with similar surface fluxes can produce simultaneous strong signatures of O_2 or O_3 and CH_4, CH_3Cl or N_2O.

Biosignatures may be easier to detect on planets orbiting M dwarfs



Segura et al., 2003, 2005

CH_4, N_2O, CH_3Cl have longer lifetimes

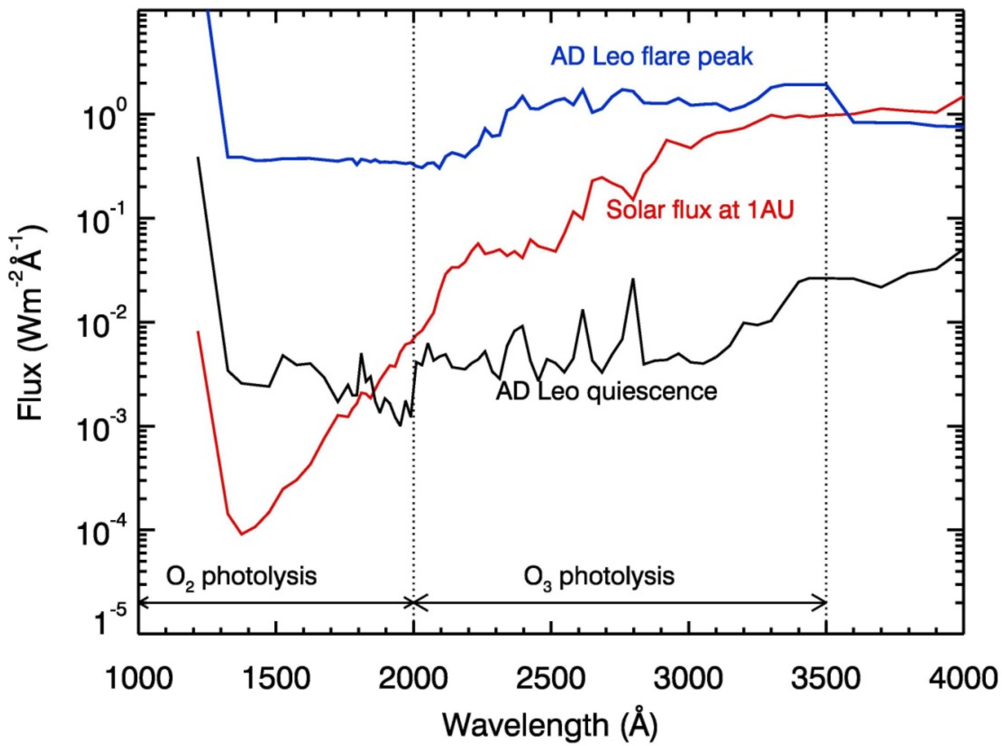
Why enhanced CH_4 for planets around M Dwarfs?

CH_4 destruction on Earth

$O_2 + h\nu\ (\lambda < 240\ nm) \rightarrow O + O$
$O_2 + O + M \rightarrow O_3 + M$

$O_3 + h\nu\ (\lambda < 310\ nm) \rightarrow O_2 + O^1D$

$O^1D + H_2O \rightarrow 2\ OH$
$CH_4 + OH \rightarrow CH_3 + H_2O$
$CH_3 + O_2 + M \rightarrow CH_3O_2 + M$
$\rightarrow \ldots \rightarrow CO\ (or\ CO_2) + H_2O$



CH_4 photochemistry depends on the SLOPE of the UV for planets with rich O_2 atmospheres

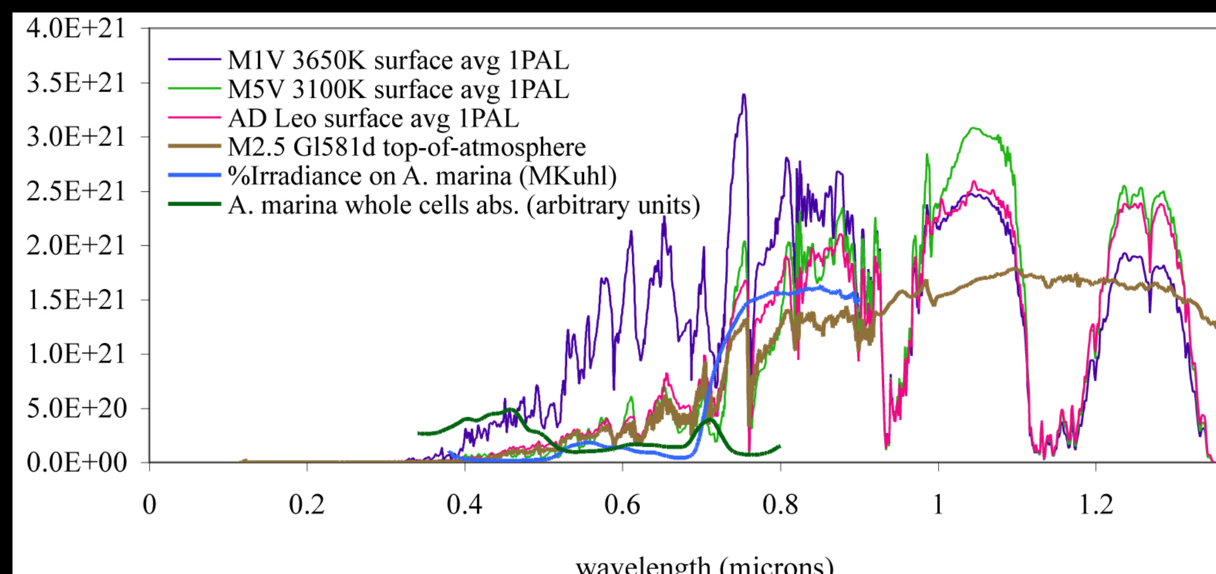
For a planet orbiting an M dwarf, a rich O_2 atmosphere may have large concentrations of CH_4 without needing large CH_4 production

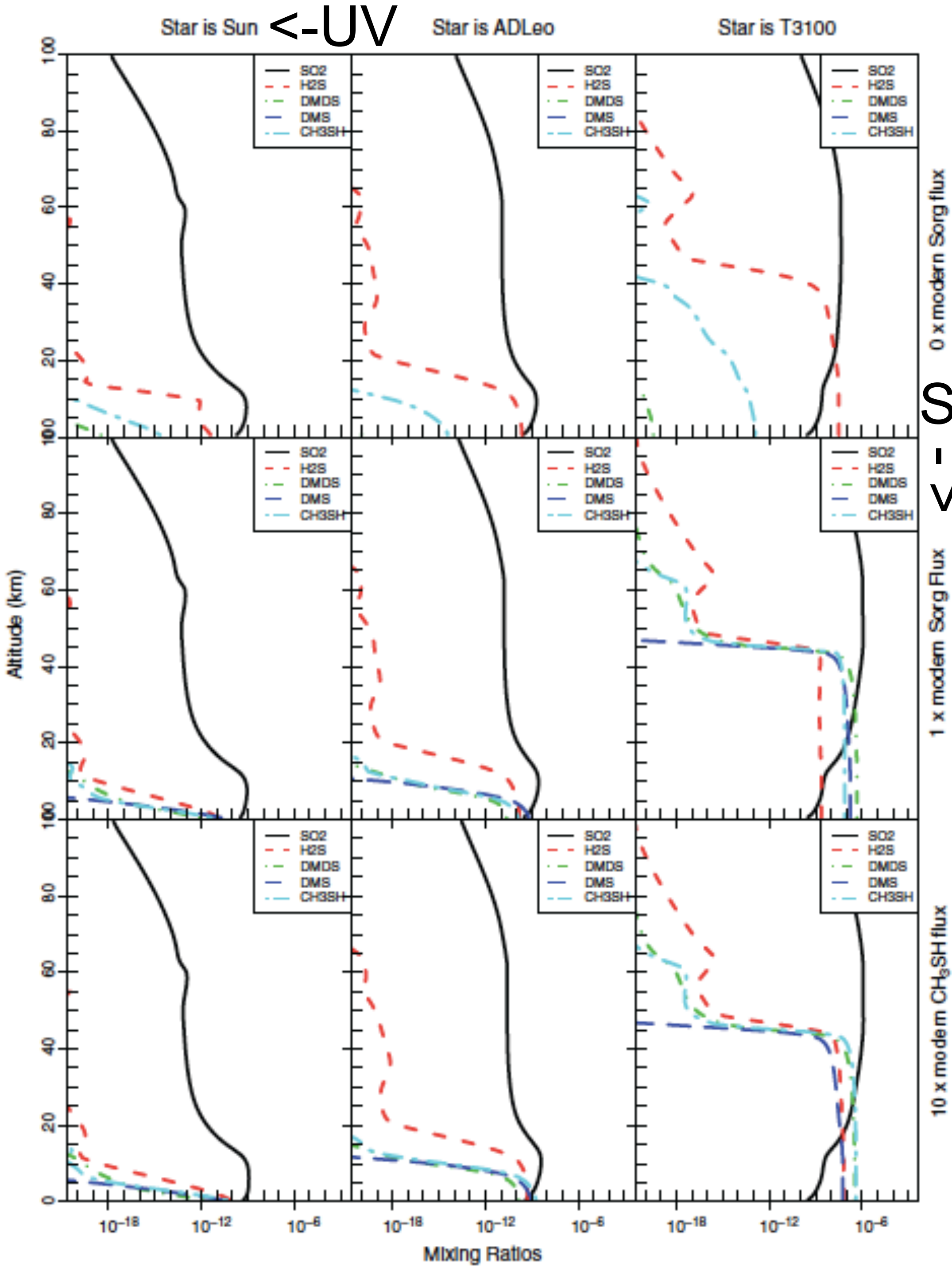
Photosynthesis on M dwarf planets?

Sufficient PAR exists, even under water!

Even for AD Leo's highest energy flare (10^{37} ergs)
UV safe at ~ 9m water depth
M dwarf still provides visible radiation 10x higher than lower limit for green plants and well above the red algae limit.

(Kiang et al., 2007a,b; Tinetti et al.,2006)





Biosignatures in Anoxic Atmospheres

- **Used a photochemical model to explore the generation of S biosignatures for an anoxic atmosphere.**

- **Early Earth atmosphere**
  - **3% CO_2**
  - **S biosphere (0,1, 10x modern)**
  - **Sun, AD Leo, T3100K**

DMS or DMDS could increase to detectable levels in cases of extremely low incident UV.

e.g. in the habitable zone of an inactive M dwarf star.

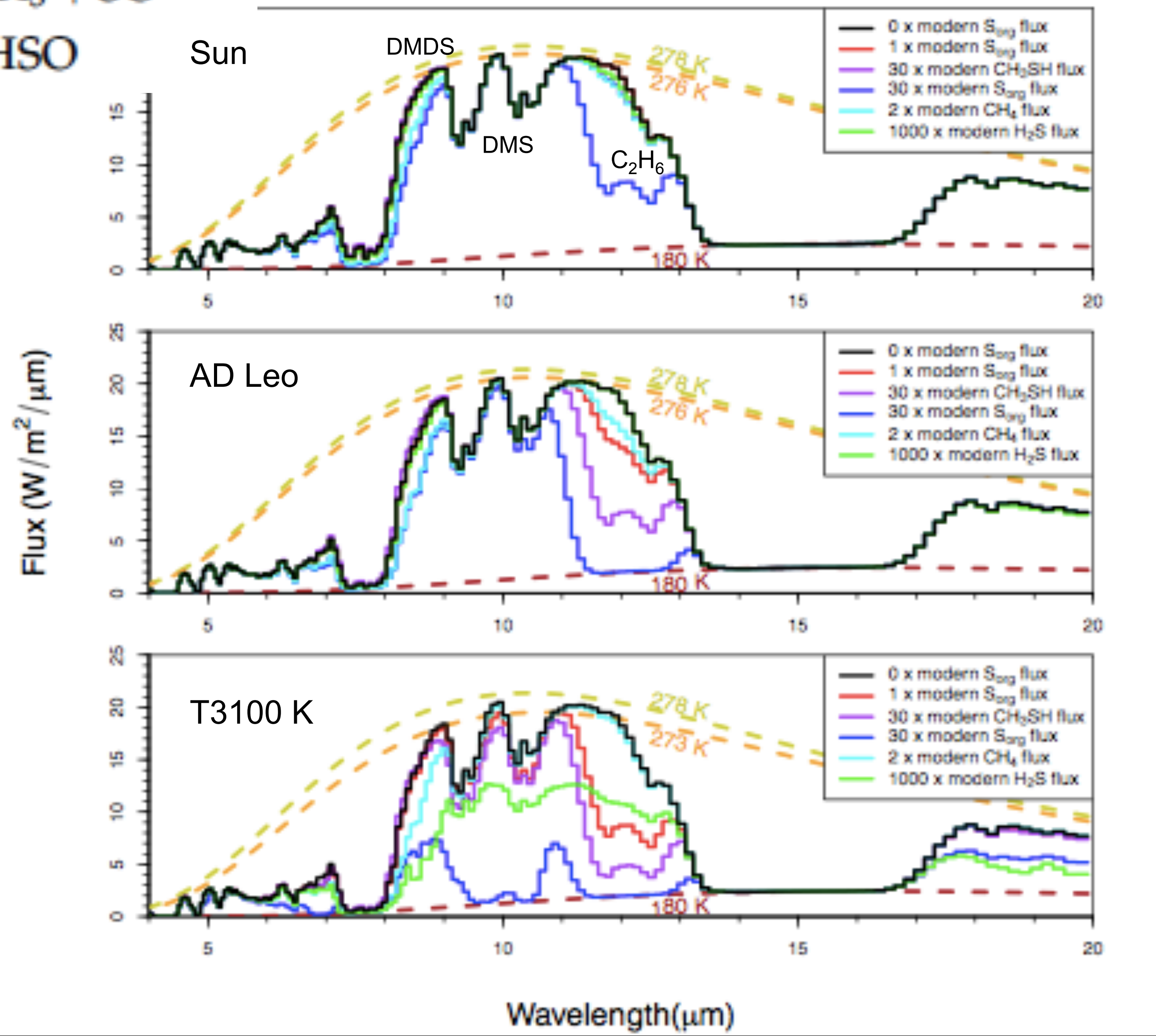
Domagal-Goldman et al., *Astrobiology*, 2011

$$C_2H_6S_2 + O \rightarrow CH_3 + SO + CH_3S$$
$$OCS + h\nu \rightarrow CO + S$$
$$C_2H_6S + O \rightarrow CH_3 + CH_3 + SO$$
$$CH_3SH + O \rightarrow CH_3 + HSO$$

The most detectable feature of the presence of organic sulfur gases is ethane.

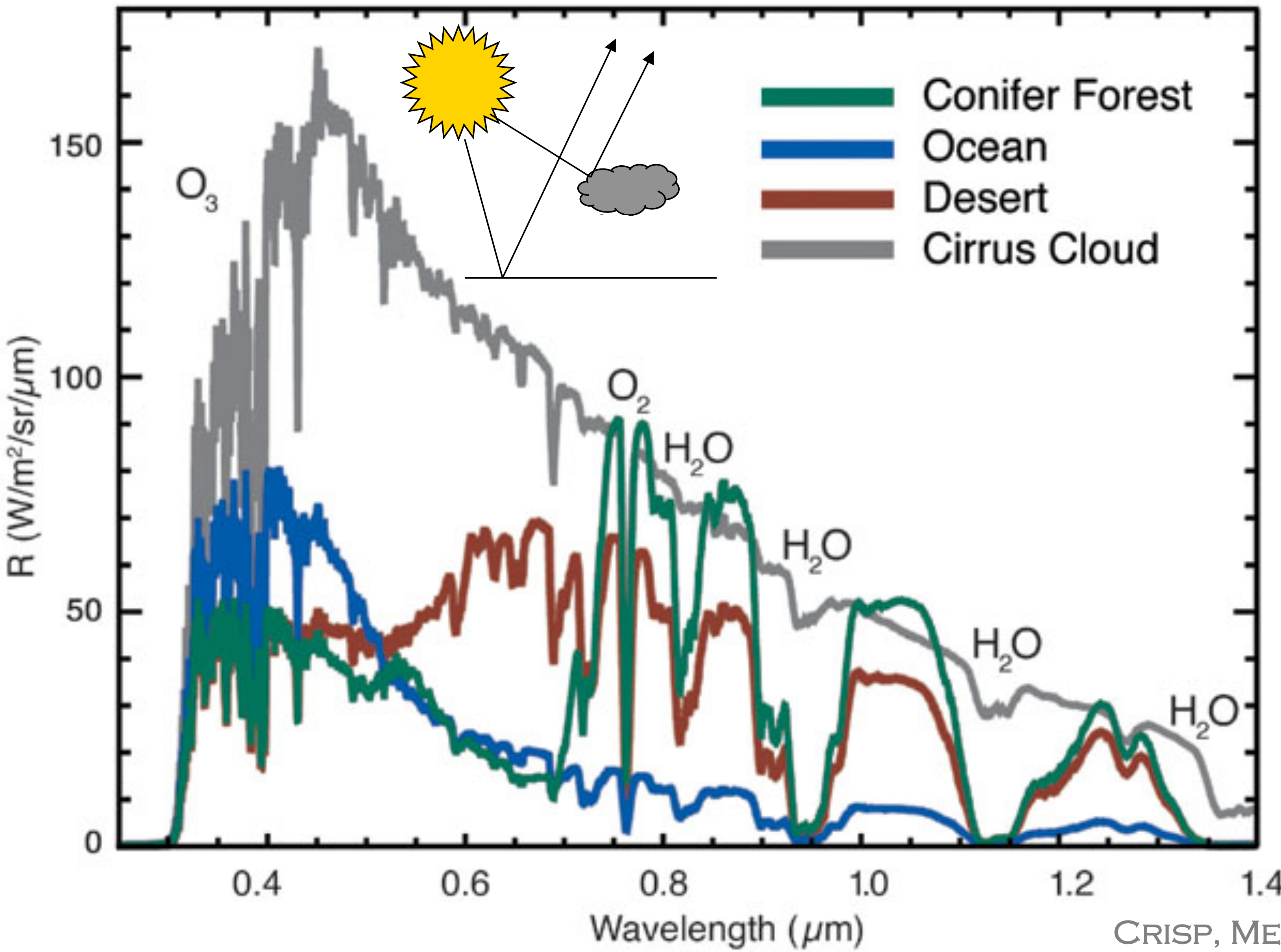
An indirect product at concentrations over those expected based on the planet's methane concentration.

Interestingly, methylation is a very common metabolic process….



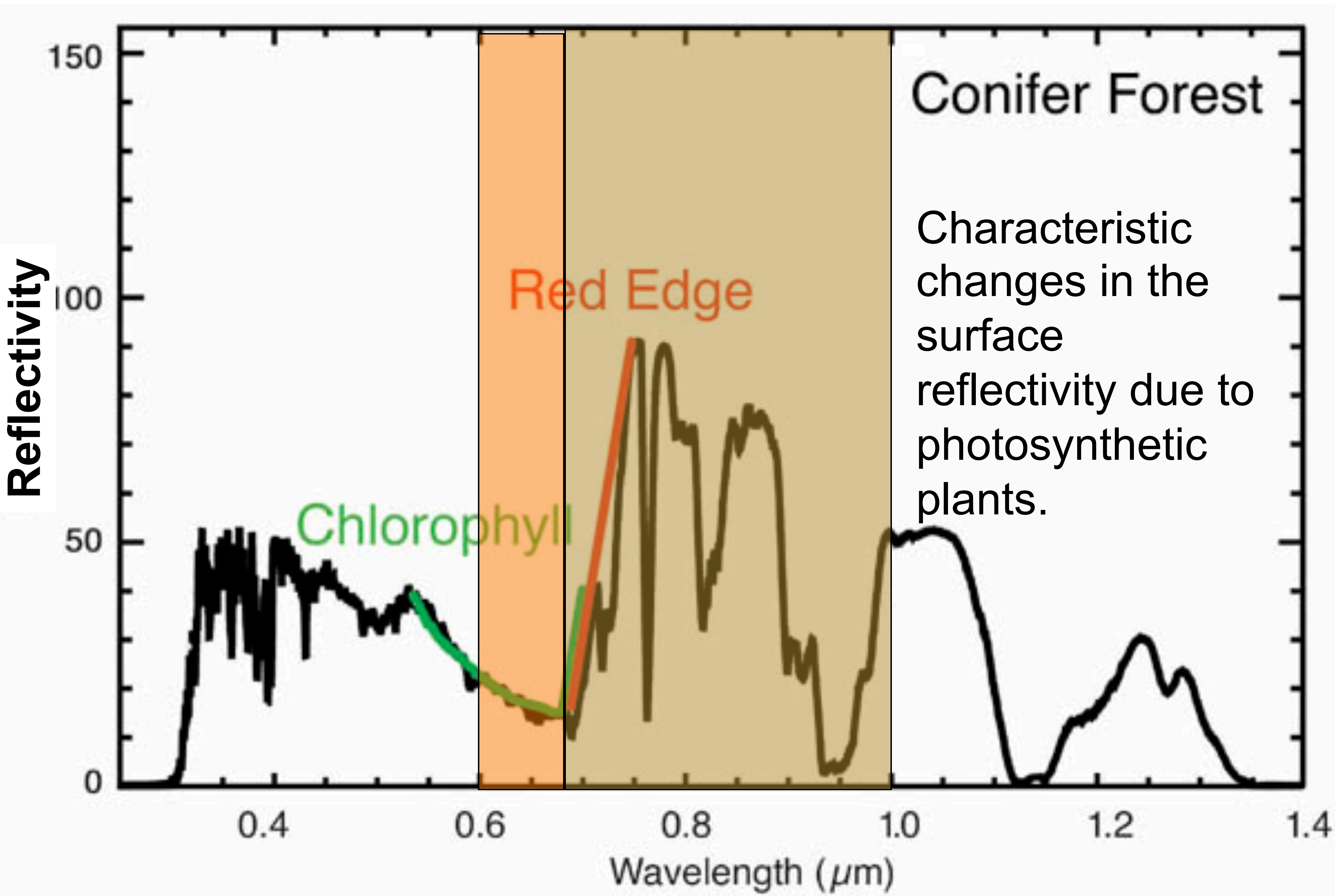
Surface Biosignatures

SURFACE BIOSIGNATURES



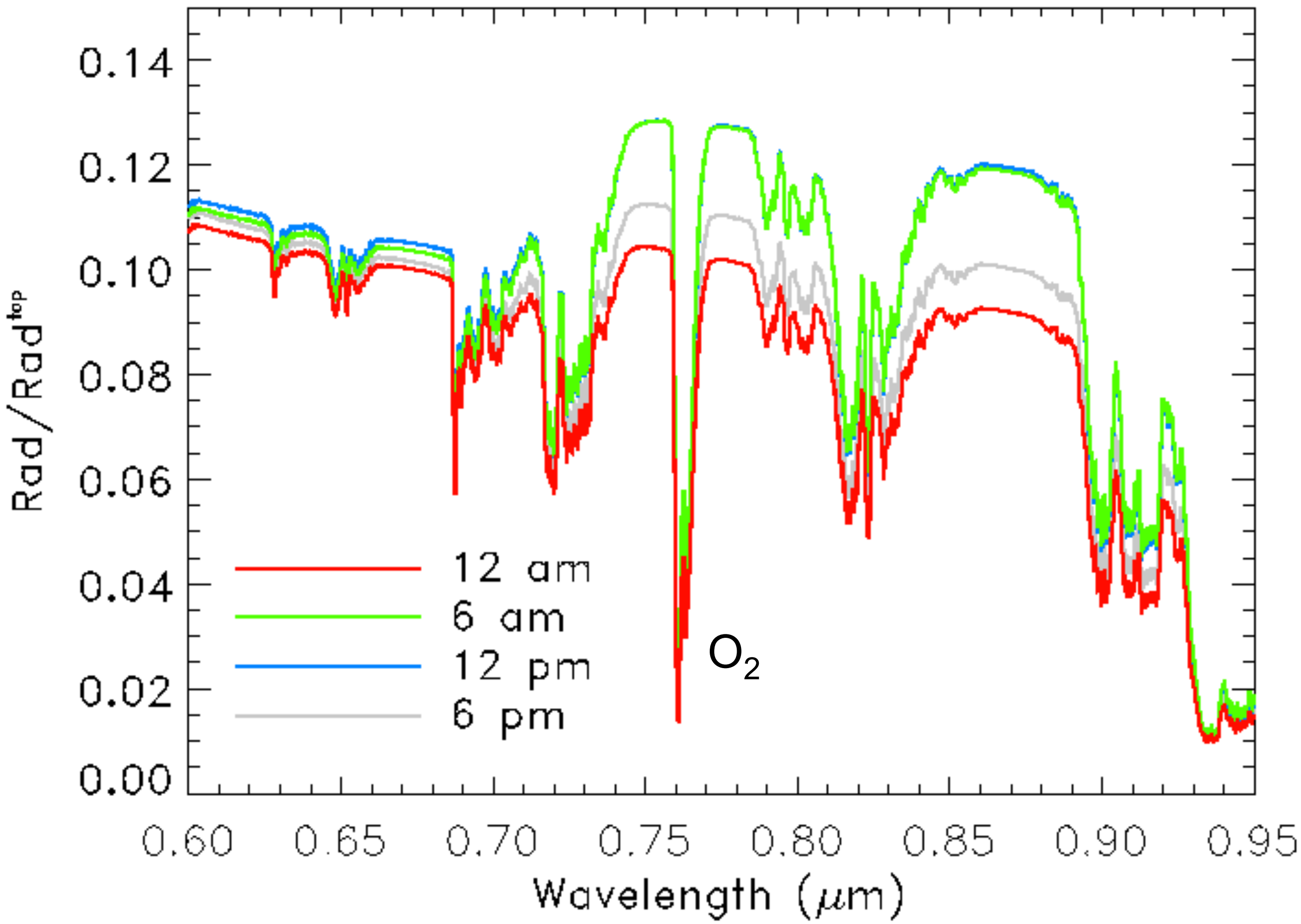
Crisp, Meadows

The Red Edge



Characteristic changes in the surface reflectivity due to photosynthetic plants.

Red-Edge with Different Cloudless Earth Views

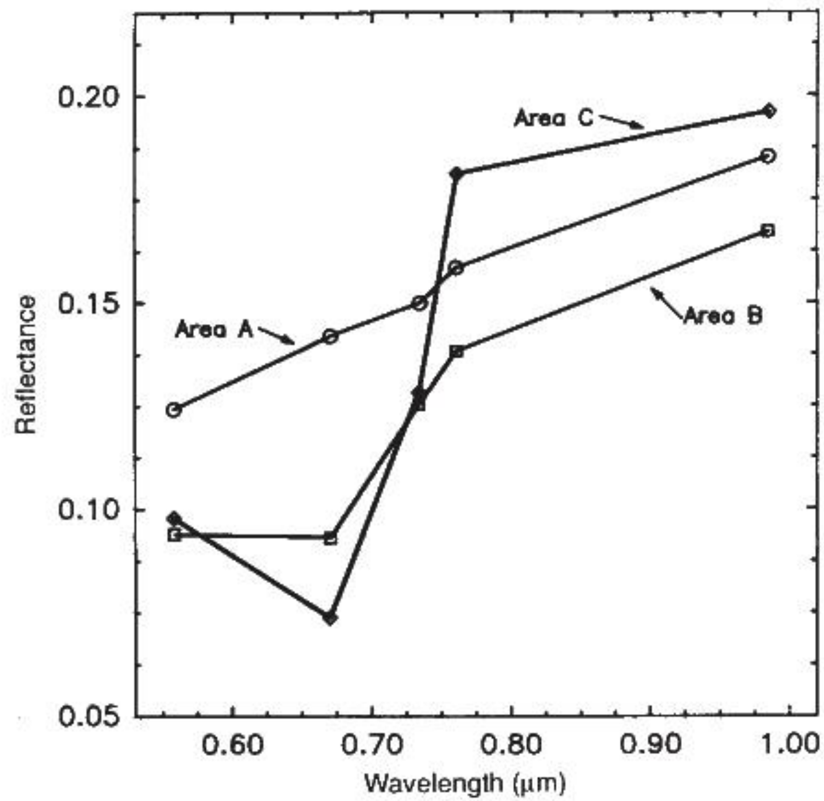


Tinetti et al., 2006

With clouds: a 2% effect

Montañes-Rodriguez et al., 2006

Galileo: Detecting Life on Earth

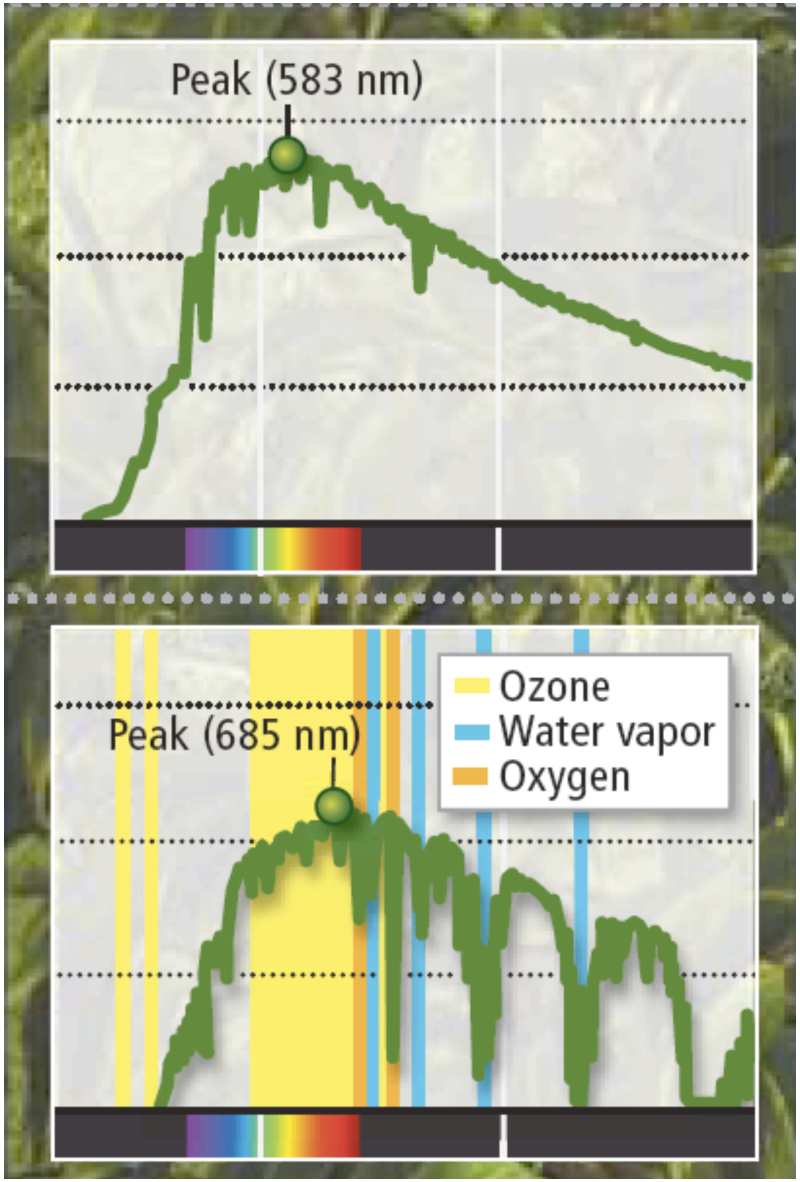


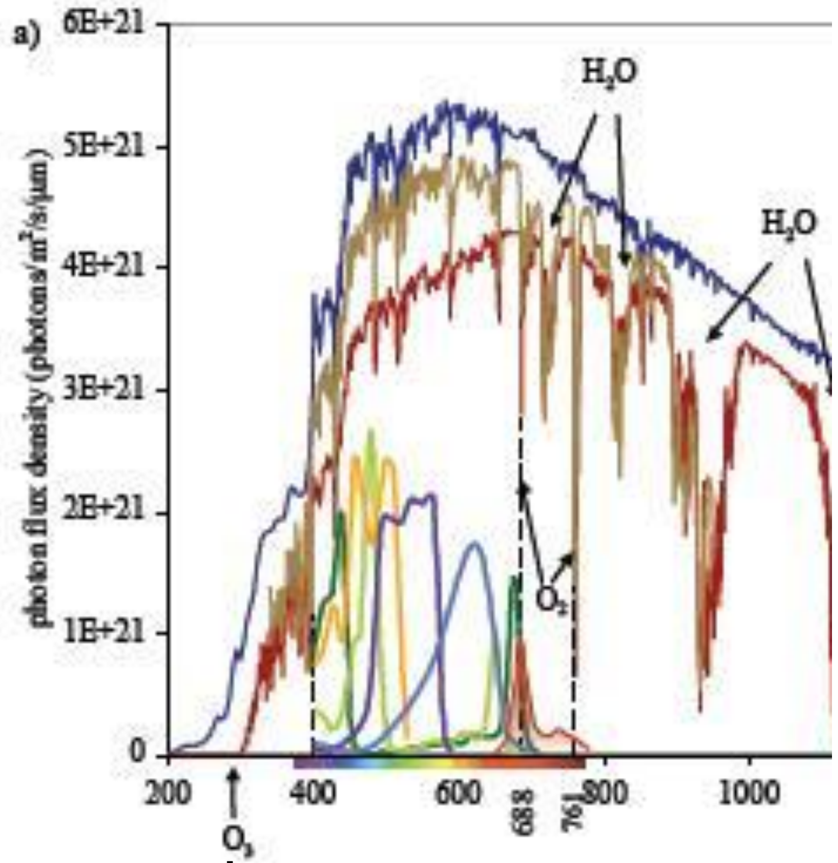
- In this experiment, they obtained broad-band filter observations across the visible and NIR, for three places on the planet.

Sagan et al., 2003

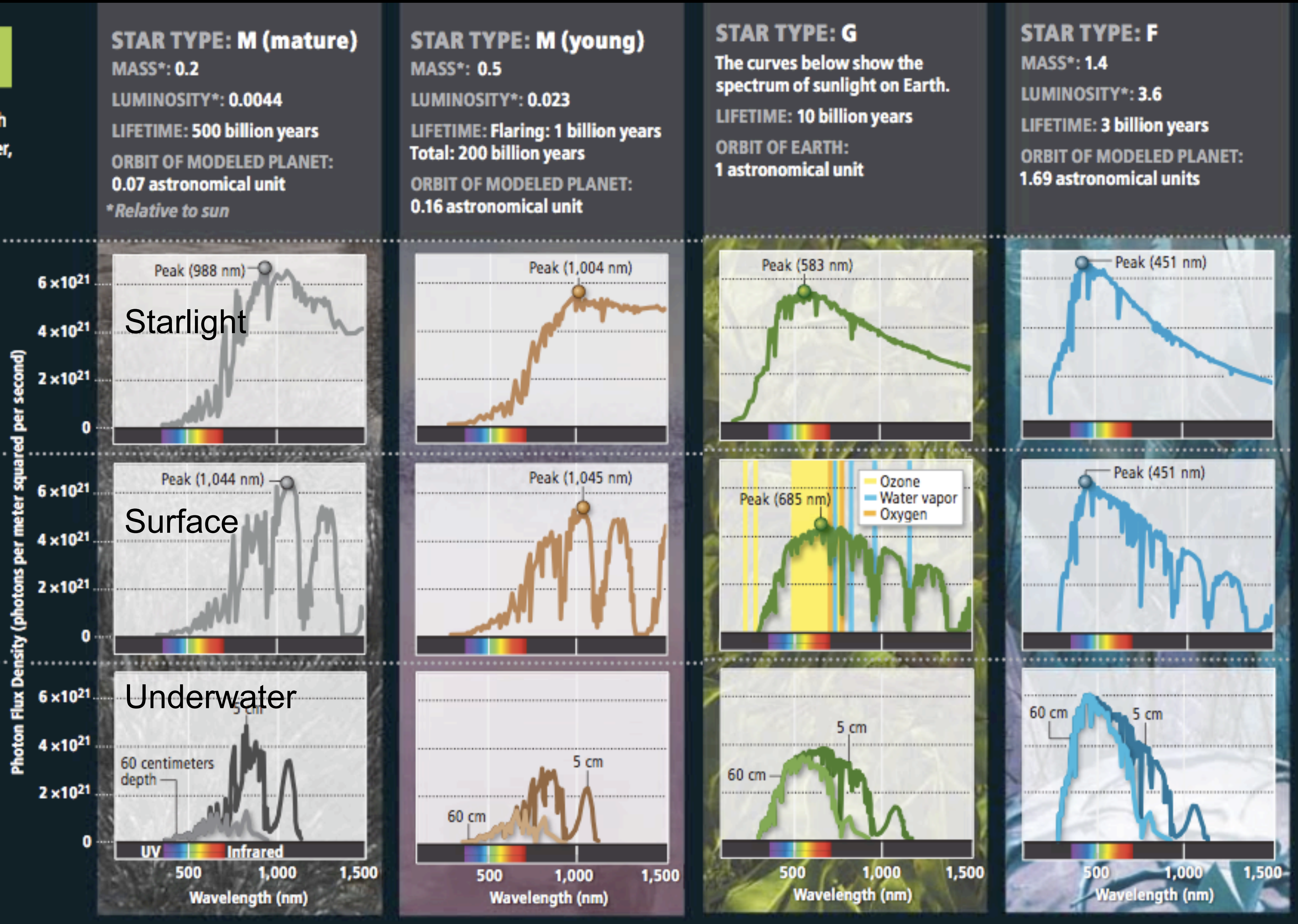
Predicting Photosynthetic Biosignatures

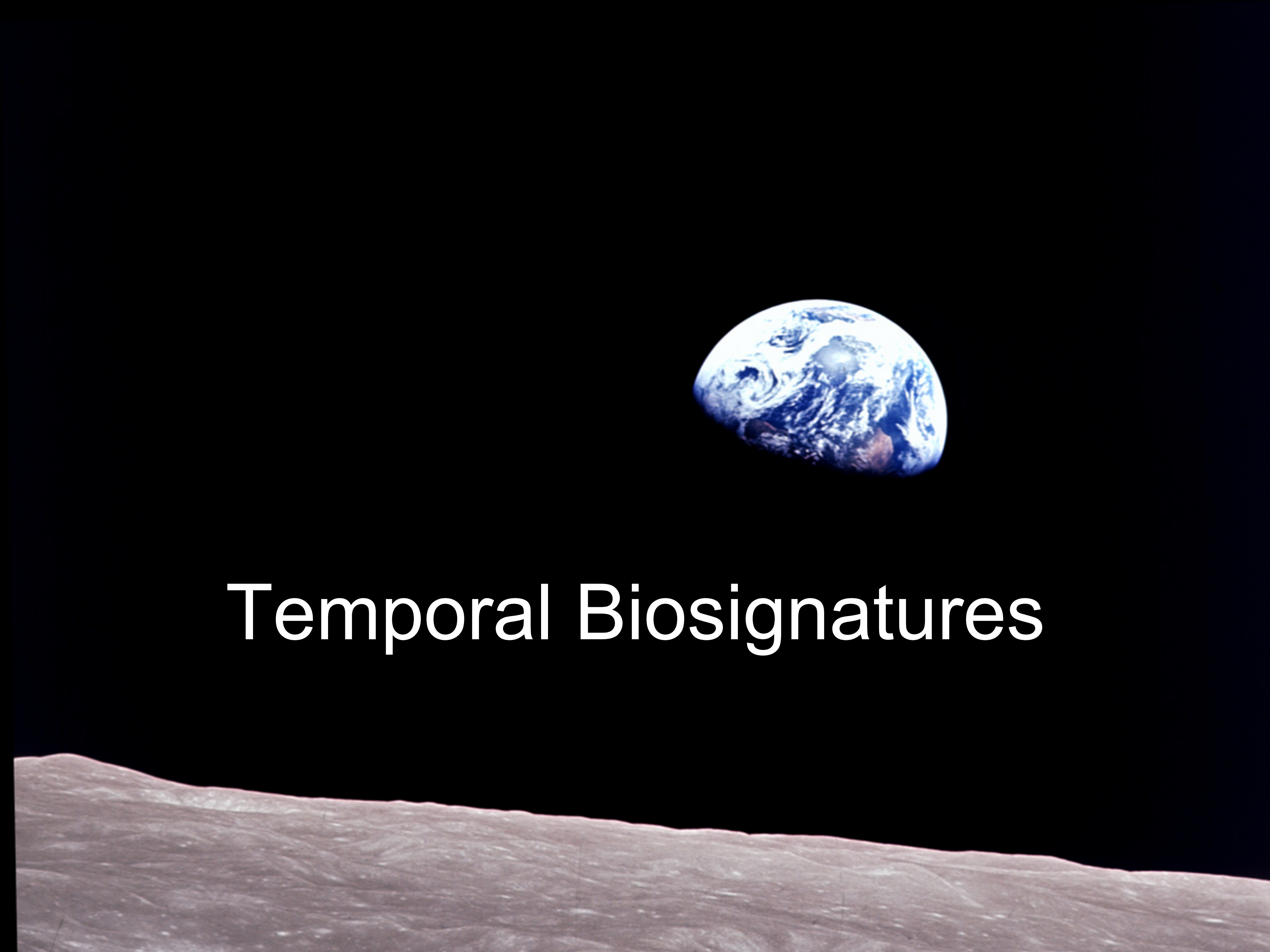
Kiang et al., *Astrobiology*, 2007b; Kiang, *Scientific American*, 2007)



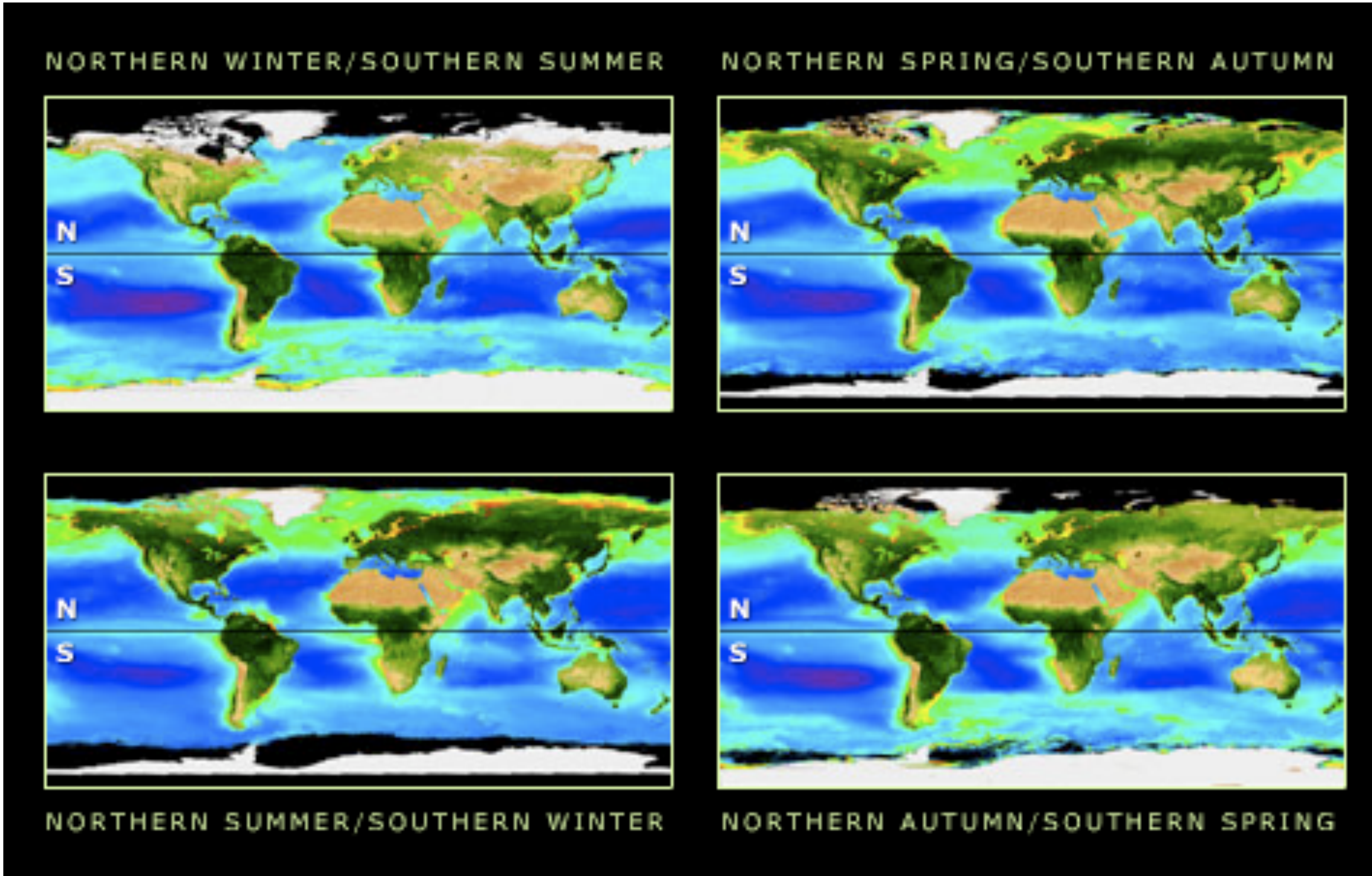


At the Earth's surface, blue light is the highest energy, but thanks to ozone, the largest number of photons reaching the surface are red. For photosynthesis, plants use the highest energy and most plentiful, selecting against green photons.


STAR TYPE: M (mature)
MASS*: 0.2
LUMINOSITY*: 0.0044
LIFETIME: 500 billion years
ORBIT OF MODELED PLANET: 0.07 astronomical unit
*Relative to sun
STAR TYPE: M (young)
MASS*: 0.5
LUMINOSITY*: 0.023
LIFETIME: Flaring: 1 billion years
Total: 200 billion years
ORBIT OF MODELED PLANET: 0.16 astronomical unit
STAR TYPE: G
The curves below show the spectrum of sunlight on Earth.
LIFETIME: 10 billion years
ORBIT OF EARTH: 1 astronomical unit
STAR TYPE: F
MASS*: 1.4
LUMINOSITY*: 3.6
LIFETIME: 3 billion years
ORBIT OF MODELED PLANET: 1.69 astronomical units
Photon Flux Density (photons per meter squared per second)
Starlight
Surface
Underwater
Peak (988 nm)
Peak (1,004 nm)
Peak (583 nm)
Peak (451 nm)
Peak (1,044 nm)
Peak (1,045 nm)
Peak (685 nm)
Ozone
Water vapor
Oxygen
Peak (451 nm)
60 centimeters depth
5 cm
60 cm
5 cm
60 cm
5 cm
60 cm
5 cm
UV
Infrared
0
2 x10^21
4 x10^21
6 x10^21
500
1,000
1,500
Wavelength (nm)

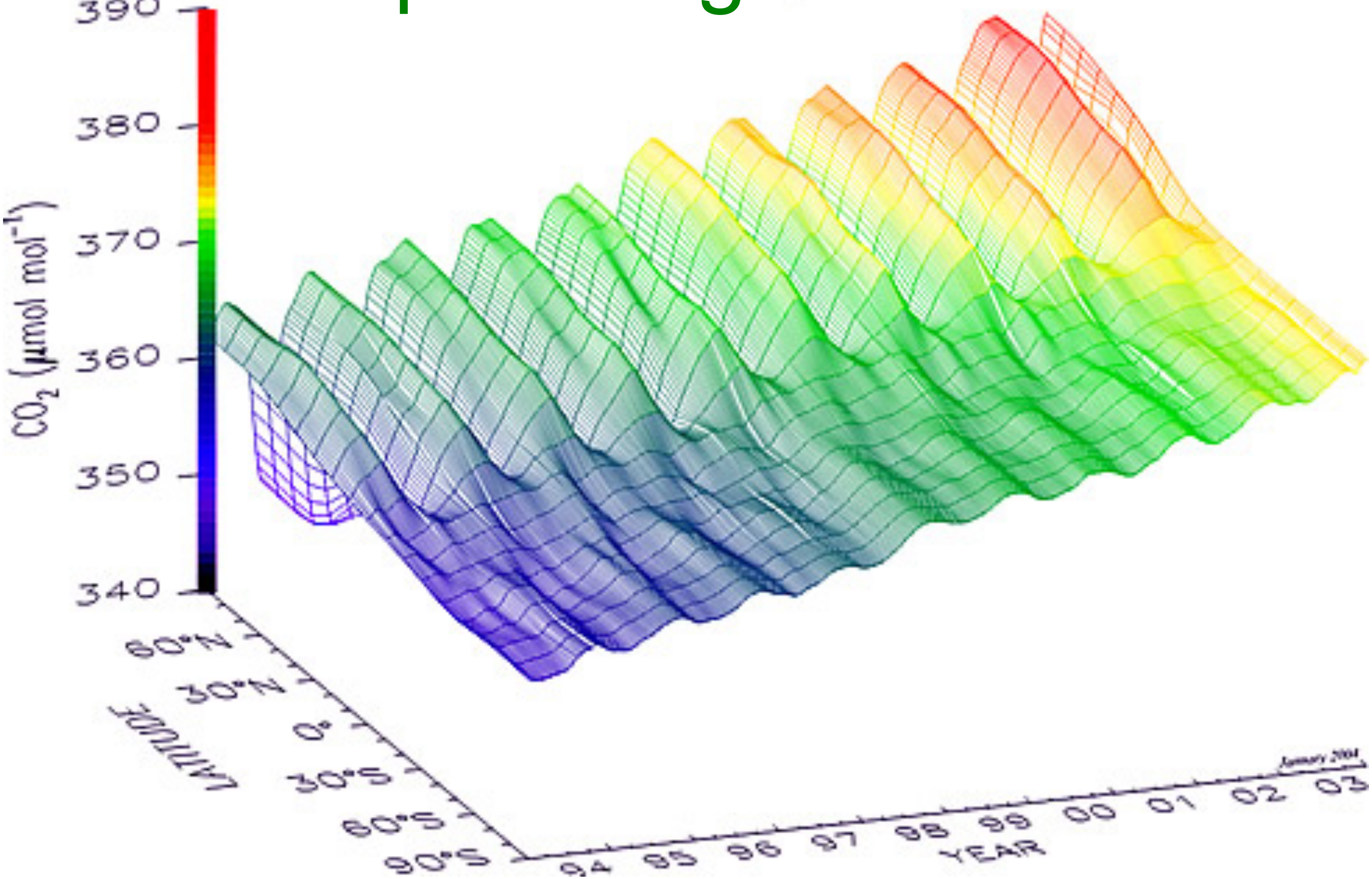

Temporal Biosignatures

Temporal Signs of Life



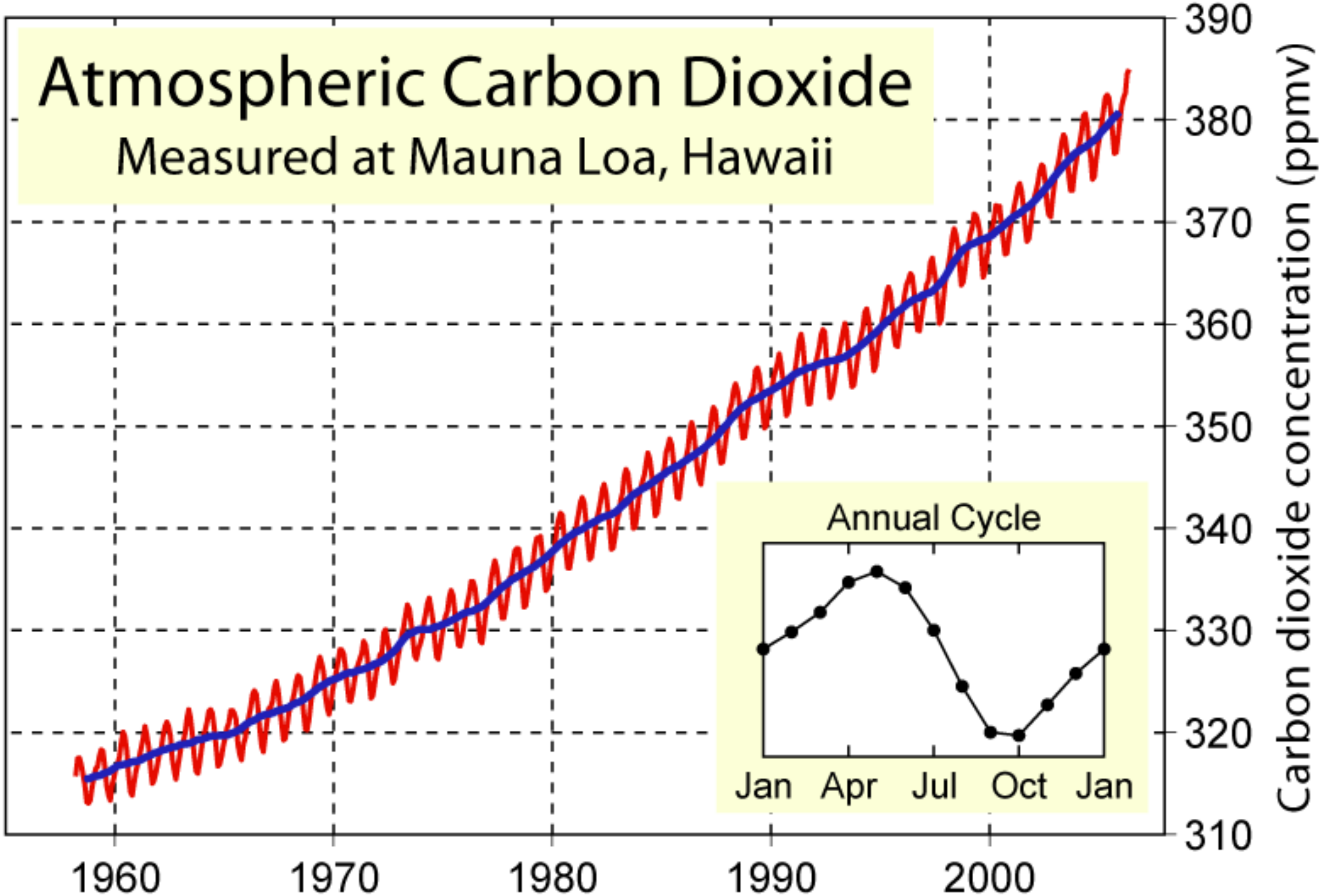
- Seasonal changes in vegetation coverage

Temporal Signs of Life



Biogenic gas signatures that change with day-night, or seasons

CO_2 as a Biosignature?



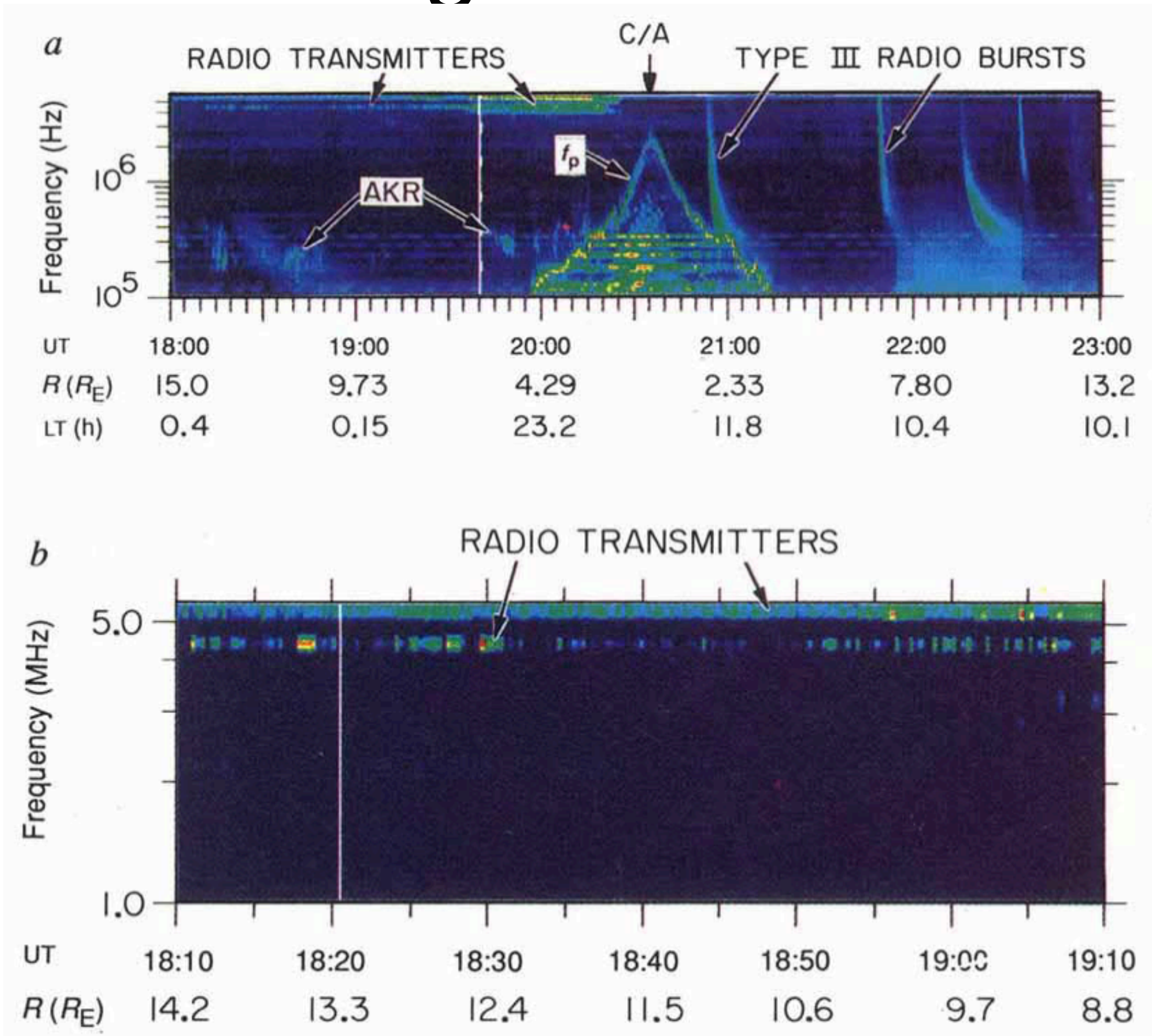
Technosignatures

Technosignatures

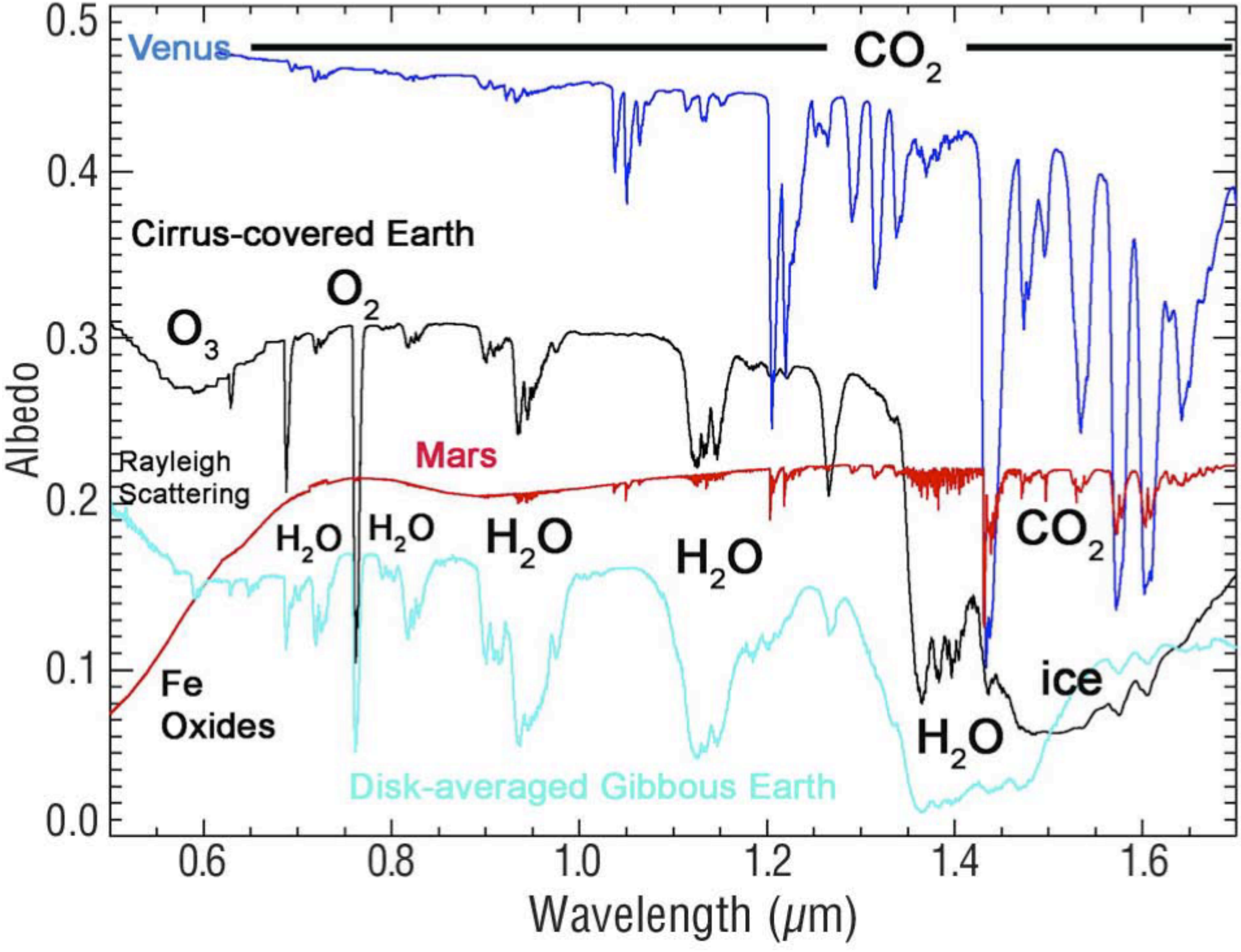
- Beacons, messages or communication sent using electromagnetic radiation
  - Radio, light or infrared waves would likely be easiest
  - Possibility of “stellarforming” the host star.
- “Rocket trails” from interstellar travel

- Astroengineering
  - Artifacts left in our own Solar System
  - Artifacts left at the Earth-Moon Lagrange points
  - Structures that gather energy from the parent star

Technosignature Detection

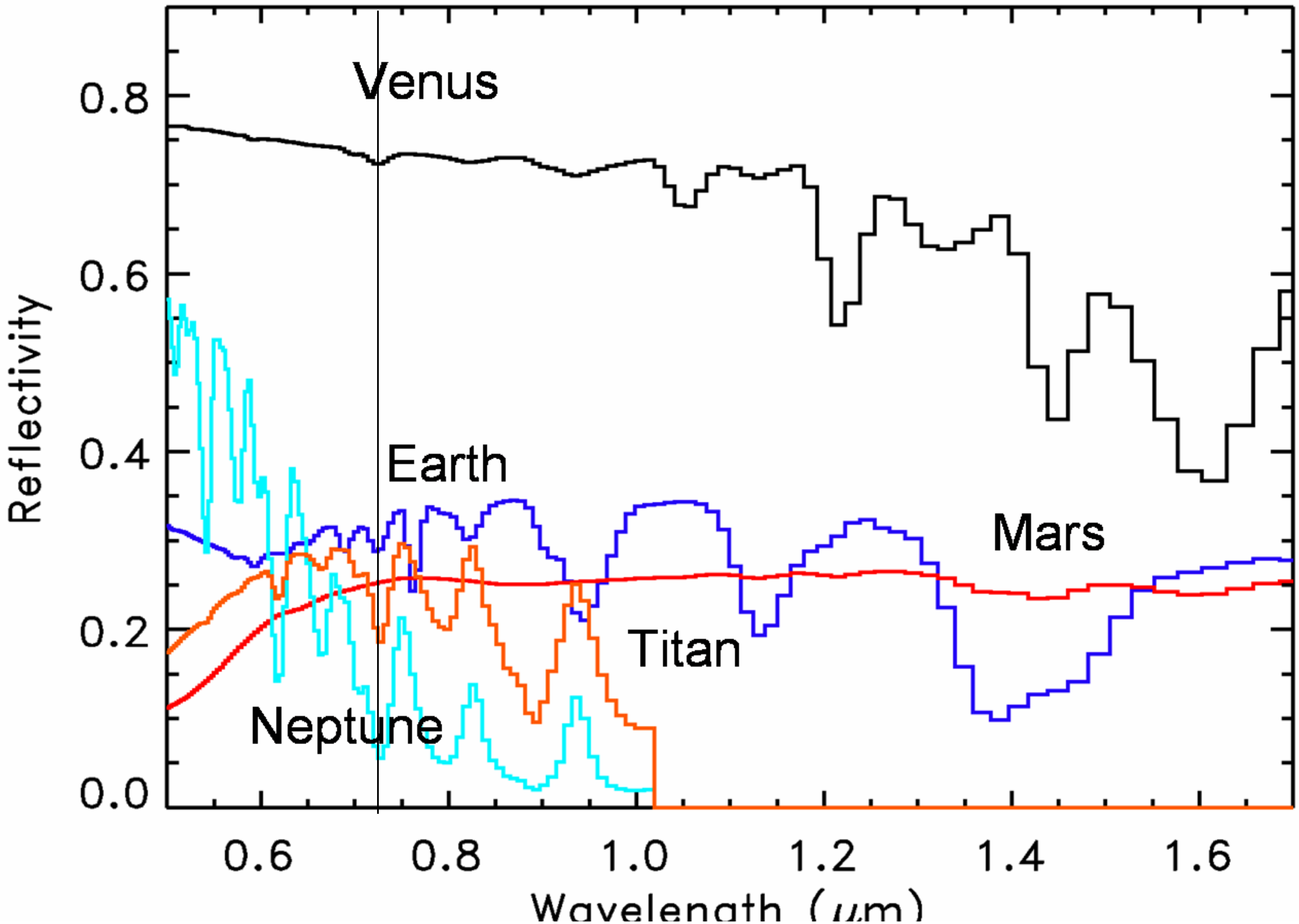


Sagan et al., 1993



Venus
CO_2
Cirrus-covered Earth
O_2
O_3
Rayleigh
Scattering
Mars
H_2O
H_2O
H_2O
H_2O
CO_2
Fe
Oxides
ice
H_2O
Disk-averaged Gibbous Earth
Albedo
Wavelength (μm)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1.0
1.2
1.4
1.6

Context is ALWAYS important!



So many worlds, so little (telescope) time…

Kiang, Scientific American, 2007